STUDY OF BEHAVIOR OF GRILLAGES IN ELASTIC AND PLASTIC RANGES

by

Thein Wah

Robert Sherman

FINAL REPORT

Contract No. N00024-67-C-5356
Project Serial No. S-F013 C3 01 Task 2050
SwRI Project No. 03-2101-01

for

Naval Ship Systems Command
Department of the Navy
Washington, D. C. 20360

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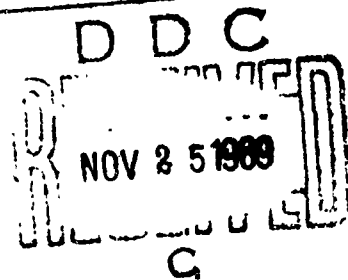# STUDY OF BEHAVIOR OF GRILLAGES
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Approved:

Robert C. DeHart, Director
Department of Structural Research

ABSTRACT

This report is concerned with an experimental evaluation of the behavior of plated grillages under the simultaneous action of a uniform normal pressure and axial compression. The combination of loads was gradually increased so as to produce large plastic deformation, the aim being to obtain an estimate of the collapse strength of the grillage.

The test procedure is described and conclusions are drawn regarding the behavior of the longitudinals, the transversals, and the plating. Difficulties in the tests arising from local crippling of the stiffeners are also discussed.

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I. INTRODUCTION

The objective of this program was to experimentally evaluate the behavior of plates grillages under the simultaneous action of a uniform normal pressure and an axial compression. This load combination, it was felt, would reasonably simulate conditions experienced by a ship bottom subjected to hull bending stresses plus the effects of hydrostatic pressure. Therefore, the overall size of the grillage, the size and spacing of stiffeners and transverse beams and the thickness of plating, etc., were chosen so as to be reasonably representative of an actual ship bottom.

In the original scheme a series of three tests on grillages of slightly different proportions was envisioned. On each grillage, extensive strain measurements were to be made so as to gain insight into the initial response in the elastic range and each test was to be carried to collapse in order to obtain a realistic estimate of the ultimate strength of the grillage. This was expected to be in the plastic range. However, only the first of the series was completed because of difficulties arising from local failures at the grillage ends. In fact, because of local failures, it is somewhat doubtful whether the grillage as a whole was loaded to its ultimate strength. As will be discussed, several attempts were made to strengthen the ends, but these attempts were not entirely successful and it is concluded that certain minor modifications of the test fixture would be required in order to obtain completely satisfactory results. One of

the difficulties (perhaps the most serious one) lies in the application of the axial compressive force which, in an actual ship, arises from hull bending with the ship bottom acting as the lower flange of a beam. Simulation of this stress by the test facility consisted of axial compression of the grillage by means of hydraulic jacks. This presented a problem as to the smooth transfer of load into the stiffeners and grillage plating and was not achieved without concentration of the jack load in the end panel adjacent to a moveable beam interposed between grillage and the hydraulic jacks.

It is believed, however, that much was learned concerning the behavior of the test specimen and of the measures which sould be taken to alleviate local crippling. Also, the test results indicated the desirability of certain modifications to the instrumentation plan and to the test program itself. These modifications, along with recommendations for future tests, are discussed in Appendix A of this report.

II.   DESCRIPTION OF TESTS

Although it was originally intended to run a single test on the

first grillage from initial loading to collapse, the actual procedure

evolved into a five step process, viz.: (1) initial test, (2) modification,

(3) second test, (4) second modification and (5) a third test.   The tests

shall be referred to as Tests 1(a), 1(b) and 1(c), respectively.   The test

fixture used was the same in all three tests, but certain changes were

made in the manner of application of the lateral pressure and, as pre-

viously noted, modifications were made prior to Tests 1(b) and 1(c) in

order to minimize local crippling in the test specimen ends.

The basic configuration of the test fixture is shown diagrammati-

cally in Figure 1.   The base of the fixture consists of eight - 14 x 14-1/2

inch wide flange beams (at 136 lbs/ft), 25 feet long.   Over the region to

be occupied by the grillage, there are ten - 3/4 inch plates 12 inches

high; these are placed on edge and tack welded to the top flange of the

base beams.   A 3/4 inch plate 18 feet x 10 feet then lies above the 12 inch

plates, thus forming the base for the specimen.   A 3/16 x 2-1/2 inch seal

back-up strip is welded all along the periphery of the base plate, thus

forming a seat for the grillage specimen and a cavity into which a fluid

may be introduced for the purpose of producing normal pressure.   A

liquid tight seal is provided by a rectangular rubber section which bears

against the seal back-up strip, Test 1(a), or, as was used during Tests

1(b) and 1(c), by a rubber bag lying between base plate and specimen.

FIXED END
SUPPORT

SPECIMEN
SEE SEPARATE
SKETCH

$\frac{3}{4}$" THK. SPECIMEN
BASE PLATE

BASE PLATE SUPPORT
PLATES (OR BOX BEAMS)

SIDE L'S

MOVABLE END
OF SPECIMEN

14 $\frac{5}{8}$ WF BASE BEAM

FIXED END
SUPPORT

8 DIA. 12" STROKE
HYDRAULIC CYLINDER (5)
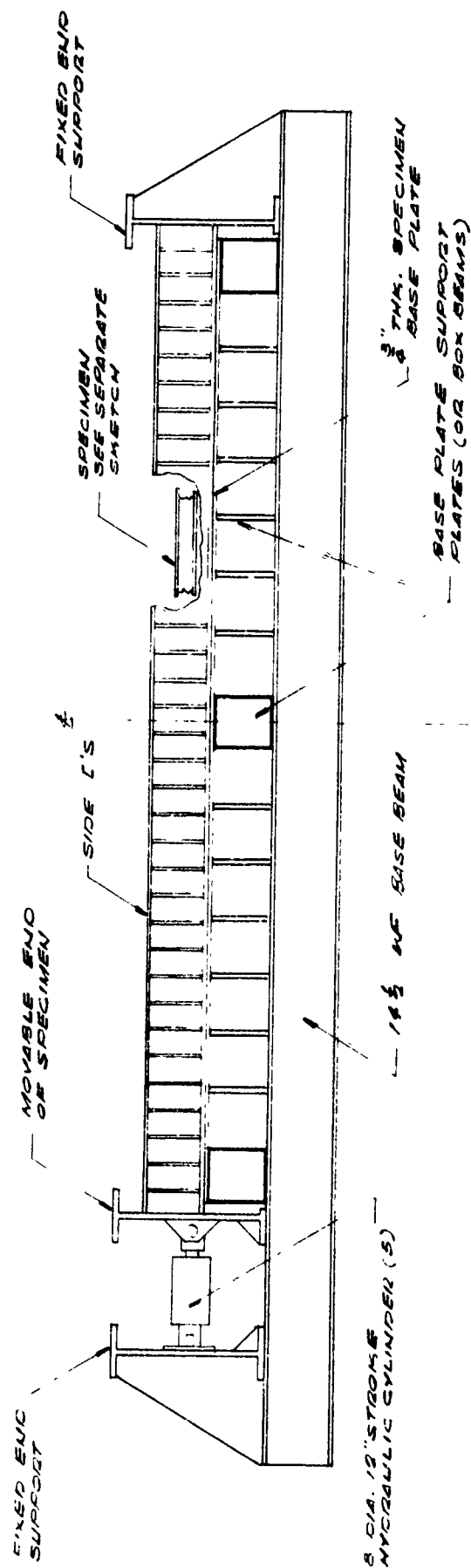
FIGURE 1. SKETCH OF THE GRILLAGE TEST FACILITY

The two ends of the fixture are closed by 30 inch I-beams, one of which is moveable and forms the end at which the axial compression is applied; the opposite end is fixed. The two longitudinal sides are closed by stiffened side channels which bolt through the specimen to the 3/4 inch base plate. Longitudinal motion is made possible by cutting 3 inch slots in the specimen, thereby allowing relative motions between the test grillage and the 3/4 inch base plate and side channels.

After the grillage specimen is placed inside the fixture, the entire top is covered by a 1-1/2 inch plate bolted with shoulder bolts to the top flanges of the 30 inch I-beams. This plate is sized to ensure that the axial load is reacted equally between base beams and cover plate. The axial load is applied by five 8 inch diameter hydraulic cylinders capable of exerting a total of about 1,500,000 pounds at a jack pressure of 6,000 psi.

Figure 2 shows a photograph of the test rig with grillage specimen in place and top cover plate removed. Figure 3 shows "Crow's feet" which were added to the transverse tees after preliminary pressurization indicated that the grillage would tear out along the clamped sides. Also, a short bar, which holds down the flange of the transverse tees, may be seen. Figure 4 shows the cover plate in place and the grillage ready for test.

The grillage specimen tested was nominally the same in Tests 1(a), 1(b), and 1(c) and was as shown diagrammatically in the sketch of Figure 5.

FIGURE 2.   GENERAL VIEW OF TEST RIG WITH TOP COVER REMOVED

FIGURE 3.   END DETAIL OF TRANSVERSE MEMBERS SHOWING "CROW'S FEET" AND HOLD-DOWN BAR ADDED PRIOR TO TEST 1(a)

FIGURE 4. THE GRILLAGE SPECIMEN UNDERGOING TEST

TEST FIXTURE, MOVABLE END I BEAM

10X4X17 LB/FT LIGHT BEAM, LOWER FLANGE REMOVED TO FORM A TEE

4 X 9.25 LB/FT TEE MADE BY CUTTING AN 8 X 2½ @ 6.5 LBS/FT JUNIOR I ALONG THE NEUTRAL AXIS

½" PLATE

TEST FIXTURE SIDE CHANNELS (CLAMPED)

TEST FIXTURE, FIXED END I BEAM

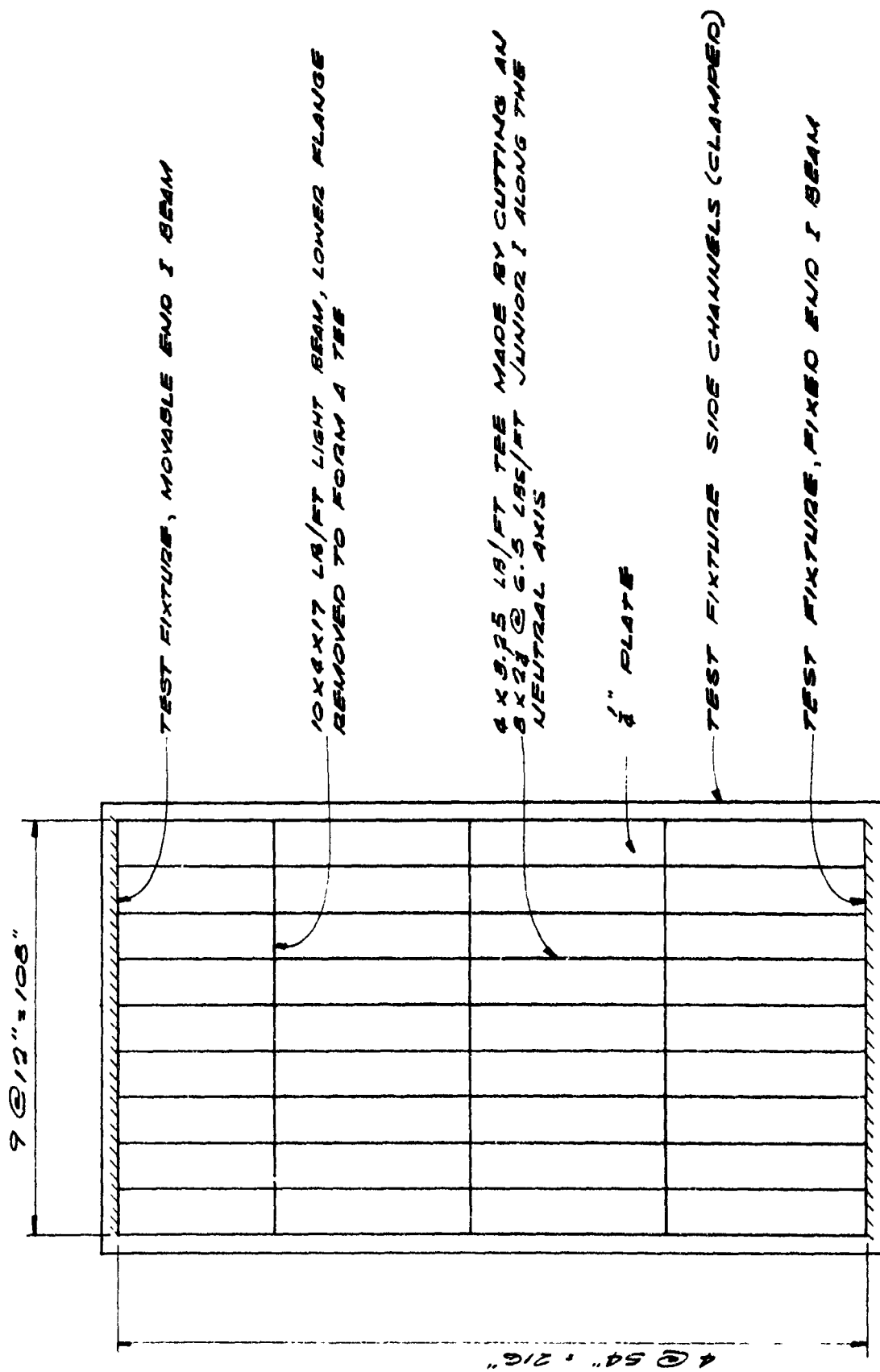9 @ 12" = 108"

4 @ 54" = 216"

FIGURE 5. SKETCH OF GRILLAGE SPECIMEN

A.   Test 1(a)

Test 1(a), the only completely instrumented test, had a total of 302 strain gages, plus several Ames dial gages, located as shown in Figure 6. During test, strain and deflection readings* were taken for ten separate combinations of axial compressive stress and normal pressure which result from design curves currently in use at the Naval Ship Systems Command. These combinations are given in Table I where they are designated as Data Points. During the tests, each Data Point was obtained by first applying the axial load to the required value, then gradually increasing the normal pressure while holding the axial load constant. When the Data Point was reached, strain and deflection readings were taken and recorded. Also, in the case of Data Points 5, 6 and 7, intermediate readings were taken at values of 1/3 and 2/3 of the required normal pressure. As will be seen from Figure 4, deflection readings were obtained along one of the beams near the longitudinal centerline of the grillage and along the beam which forms the central transversal. The resultant readings are plotted in Figures 7(a) and (b).

The most severe condition to which the grillage was subjected was a maximum axial pressure of 32,000 psi with a normal pressure of twelve psi. At this load the deflections experienced by the grillage were large enough to cause leakage of the fluid used to exert the normal pressure, the test was therefore discontinued.

*These readings were reported in a previously submitted document and therefore, for the sake of brevity and clarity, are not included herein except to the extent necessary for analysis of the resulting data, see Section III following.

FIGURE 6. STRAIN GAGE AND DIAL GAGE LOCATIONS FOR TEST 1

TABLE I

TEST NO. 1(a)

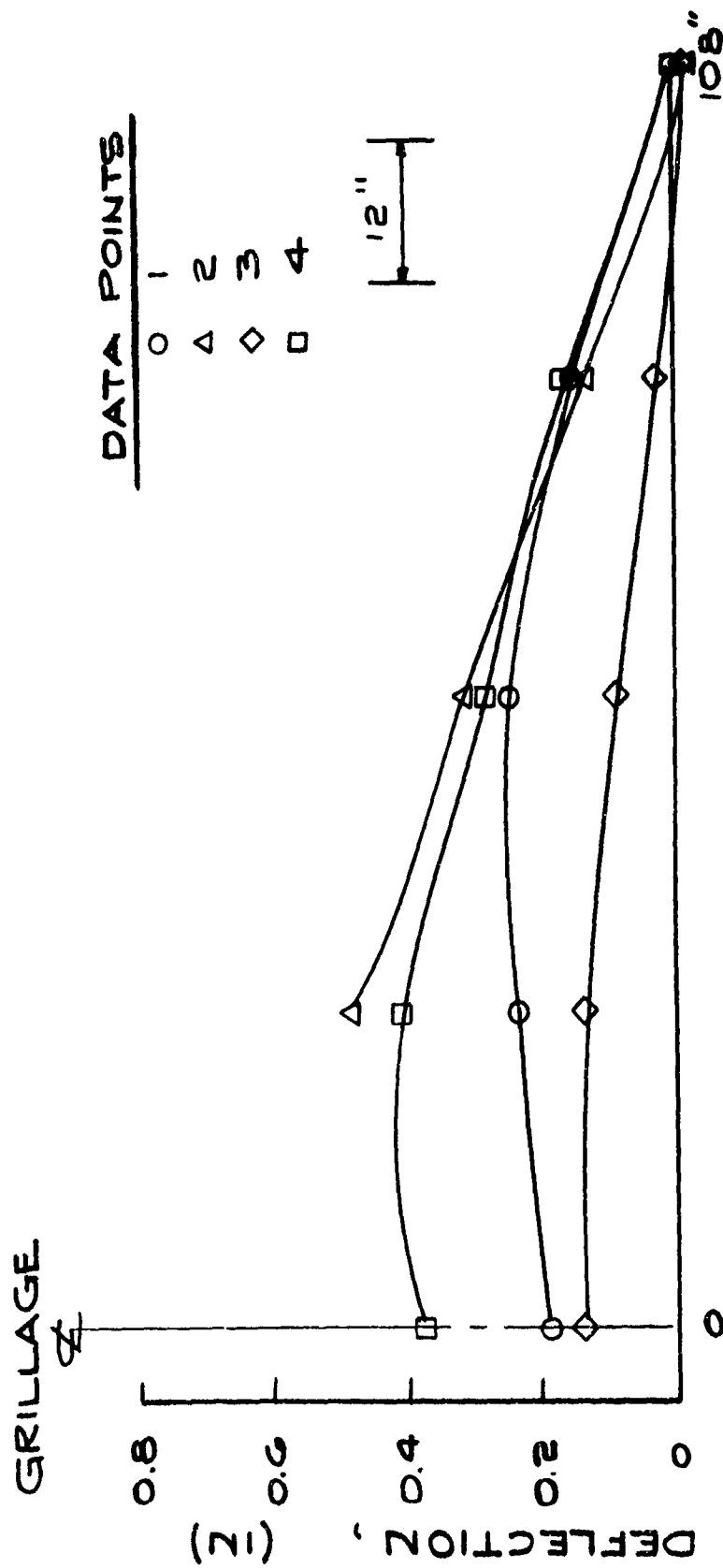| Data Point	Test Date	Primary Comp. Stress (psi)	Normal Pressure (psi)
1	6-19-68	25,000	5
2	6-20-68	21,500	10
3	7-12-68	27,750	5
4	7-12-68	25,750	10
5	7-23-68	17,750	15
6	7-23-68	24,250	15
7	7-24-68	27,750	15
8	7-31-68	29,000	12
9	7-31-68	30,000	12
10	8-1-68	32,000	12

FIGURE 7(a).   DEFLECTION OF THE GRILLAGE MEASURED ALONG
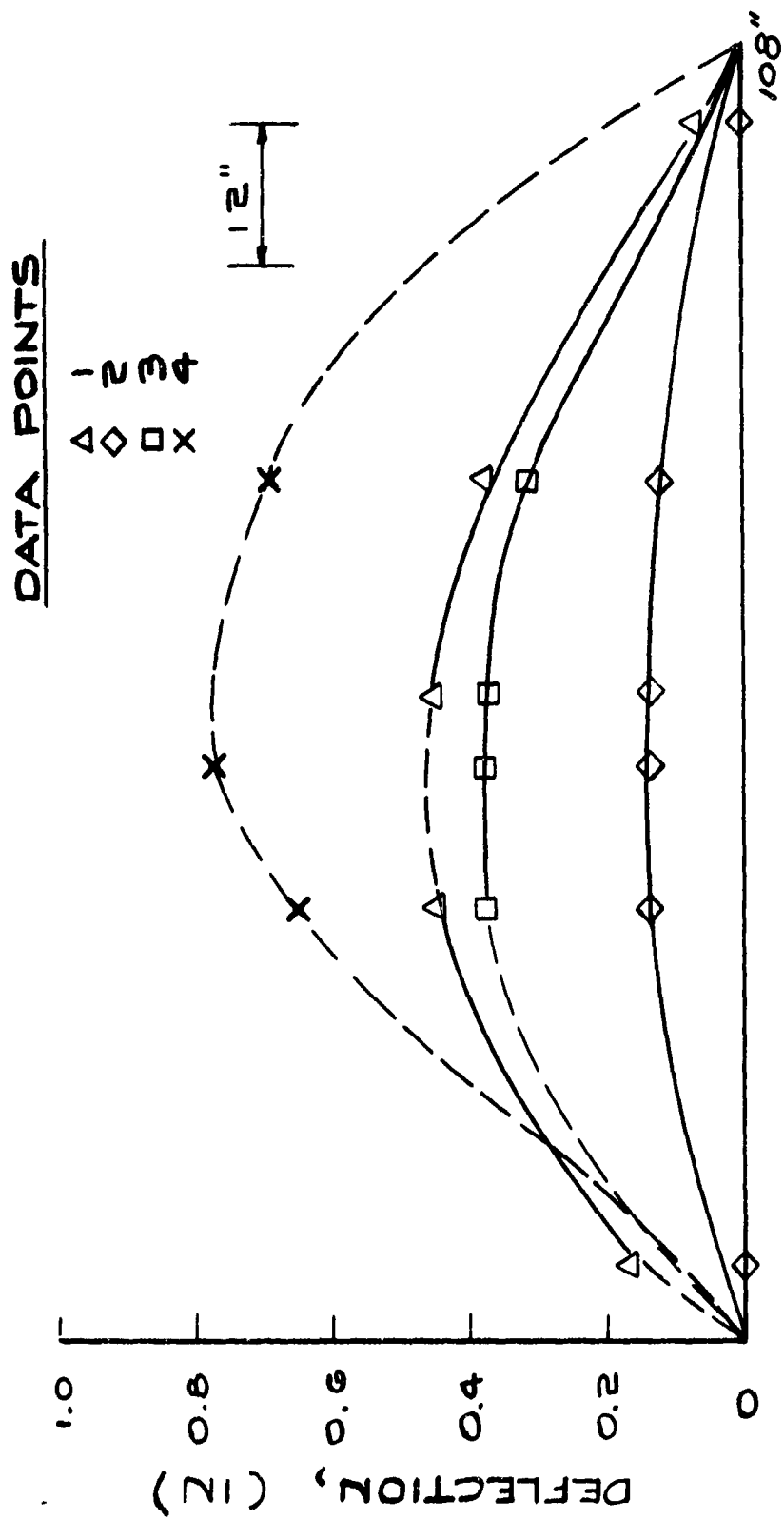LONGITUDINAL "B"

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FIGURE 7(b).   DEFLECTION OF THE GRILLAGE MEASURED ALONG
THE CENTRAL TRANSVERSAL

B.   Test 1(b)

Because Test 1(a) could not be carried far enough to cause collapse of the grillage, it was decided that a re-test should be performed using a fabric bladder 9 x 18 feet especially ordered to fit into the space under the grillage specimen. It was planned to introduce water into the bladder until the desired pressure was attained.

The procedure used in this test was to increase the lateral pressure in steps until a value of twelve psi was attained. Thereafter, the normal pressure was maintained and the axial load increased, also in steps, until the grillage could sustain no further increase in load. No strain gage readings were taken, but lateral deflections were measured at the center of the three transverse stiffeners for each pressure and/or axial load step. These results are summarized in Table II.

An examination of the grillage after test showed "failure" resulted from localized buckling of the longitudinal stiffeners at the end where the axial pressure was applied. This may be seen in Figures 8 and 9, which are overall and close-up views, respectively. In contrast to the gross buckling of the "moveable" end, the "fixed" end of the grillage, showed only a slight waviness in the stiffener flanges. This may be seen in Figure 10. The stiffeners in the two intermediate panels were virtually unaffected except for a slight ripple in one of the stiffeners in the second panel from the loading end, see Figure 11.

TABLE II

TEST NO. 1(b)

Axial* Pr. (psi)	Lateral Pr. (psi)	Defln** Gage 1 (in)	Defln** Gage 2 (in)	Defln ** Gage 3 (in)	Remarks
0	1.0	0	0	0	
10,100	1.0	.05	.05	.03	
15,000	1.0	.03	.04	.03	
20,300	1.0	.02	.04	.03	
25,000	1.0	.03	.03	.03	
25,000	6.5	.23	.30	.24	
25,000	8.0	.07	.10	.08	
25,000	10.0	.10	.14	.11	
25,000	11.0	.06	.08	.06	
25,000	12.0	.08	.14	.07	
27,200	12.0	.04	.03	.02	
30,000	12.0	.06	.09	.04	
32,450	12.0	.10	.06	.02	
33,300	12.0	-	-	-	Axial Pr. Dropped***

*Axial pressure on total cross sectional area of 37.125 in^2.

**Gages 1, 2 and 3 were along beam near longitudinal centerline at first, second and third transversals, respectively, counting from end at which axial load is applied.

***The axial pressure could not be increased beyond 33,300 psi. The longitudinal stiffeners were found to have been crippled near the points of load application.

FIGURE 8.   CRIPPLING OF THE GRILLAGE STIFFENERS AT THE
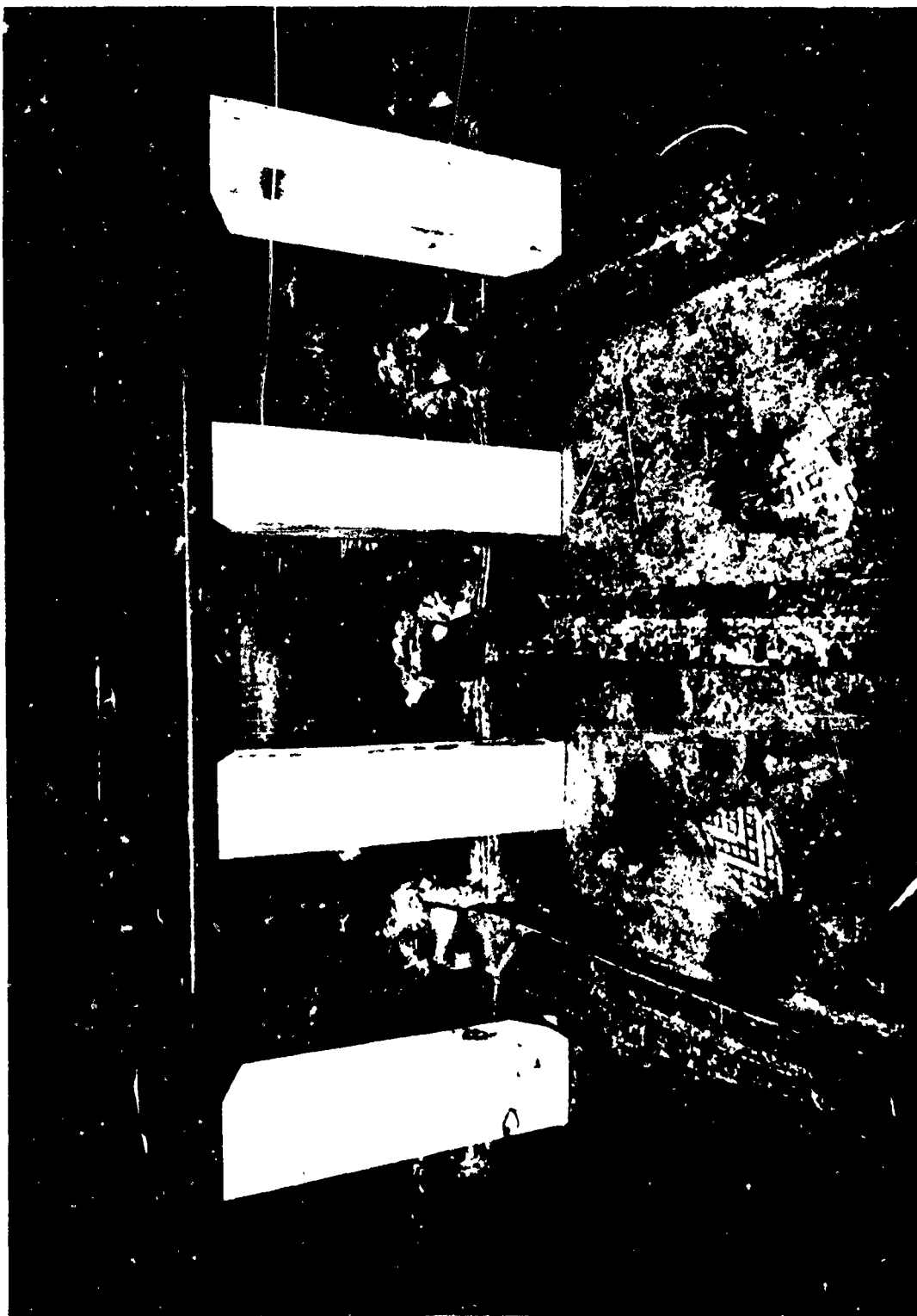LOADING END, TEST 1(b)

FIGURE 9.   CLOSE-UP OF STIFFENER CRIPPLING AT THE LOADING
END, TEST 1(b)

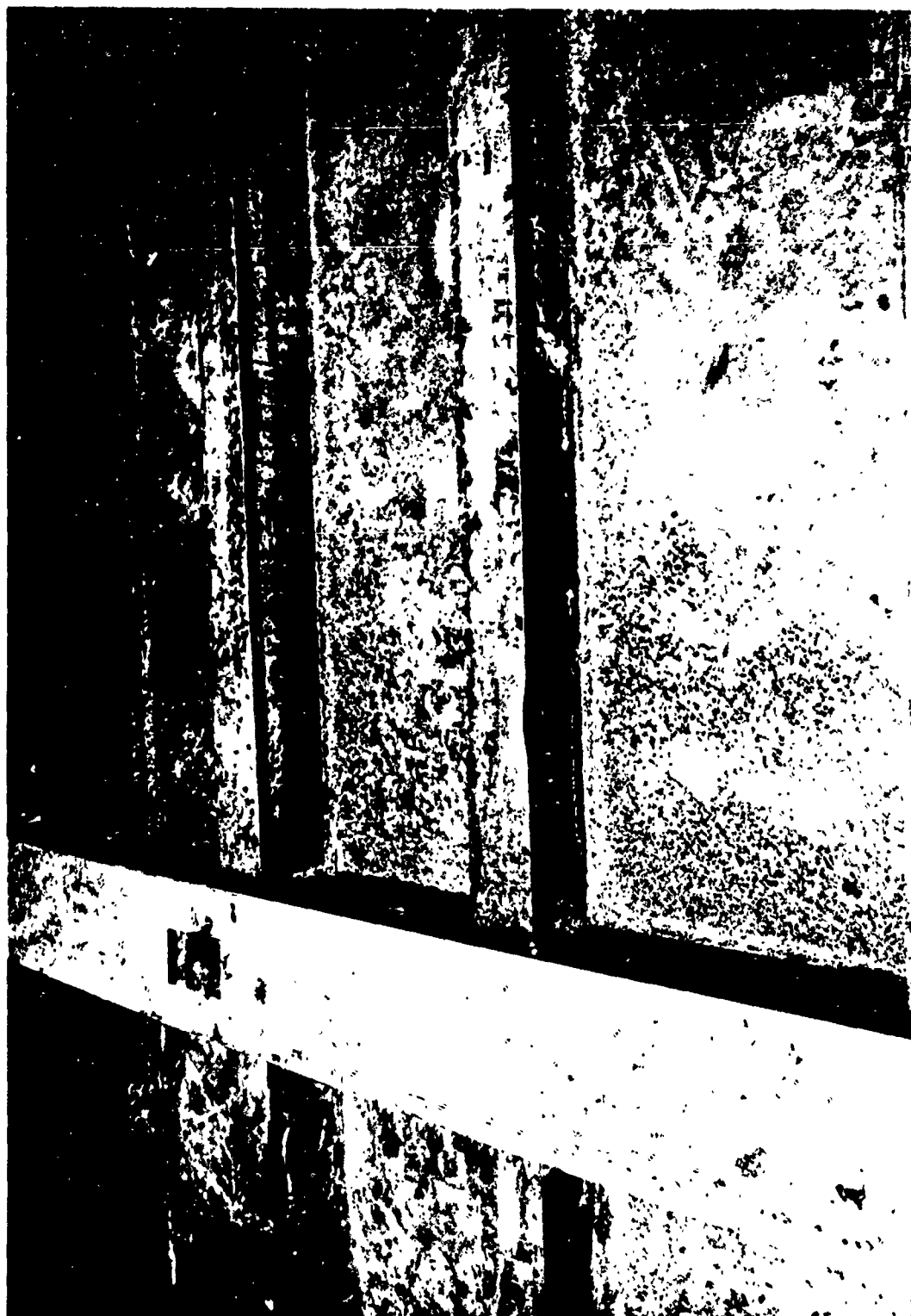FIGURE 10.   "FIXED END" OF GRILLAGE, TEST 1(b)

FIGURE 11. RIPPLE IN FLANGE AT SECOND PANEL FROM LOADING END, TEST 1(b)

C.   Test 1(c)

The results in Test 1(b) were considered inconclusive because overall collapse of the grillage did not occur. Therefore, Test 1(c) was performed in an attempt to bring about failure in one of both of the two interior bays. Such a failure mode, it was felt, would be more indicative of total collapse than was the crippling of the stiffeners in the two end bays.

To achieve this purpose, the buckled ends of the stiffeners and the crumpled grillage plating at the loading end were removed. A new section of plating was spliced into place and especially-fabricated tapered tees were welded to the plating. These tees were also welded to the cut-back longitudinals, thus providing a more gradual means of load transfer from moveable beam to the grillage specimen. This modification may be seen in Figure 12. At the fixed end of the grillage, vertically placed triangular sections were welded to the flanges and stabilized by an angle welded across the width of the grillage, see Figure 13.

As stated, the purpose of welding tapered sections was to achieve a smooth transfer of load. It was felt that to simply use heavier sections throughout the end bays would have the effect of merely transferring the load concentration further into the interior bays, thus providing results similar to those of Test 1(b) but at a different location.

The configuration of the test set-up and the test procedure was the same as in Test 1(b) except, that for Test 1(c), the normal pressure was eight rather than twelve psi. "Collapse" occurred at the axial pressure
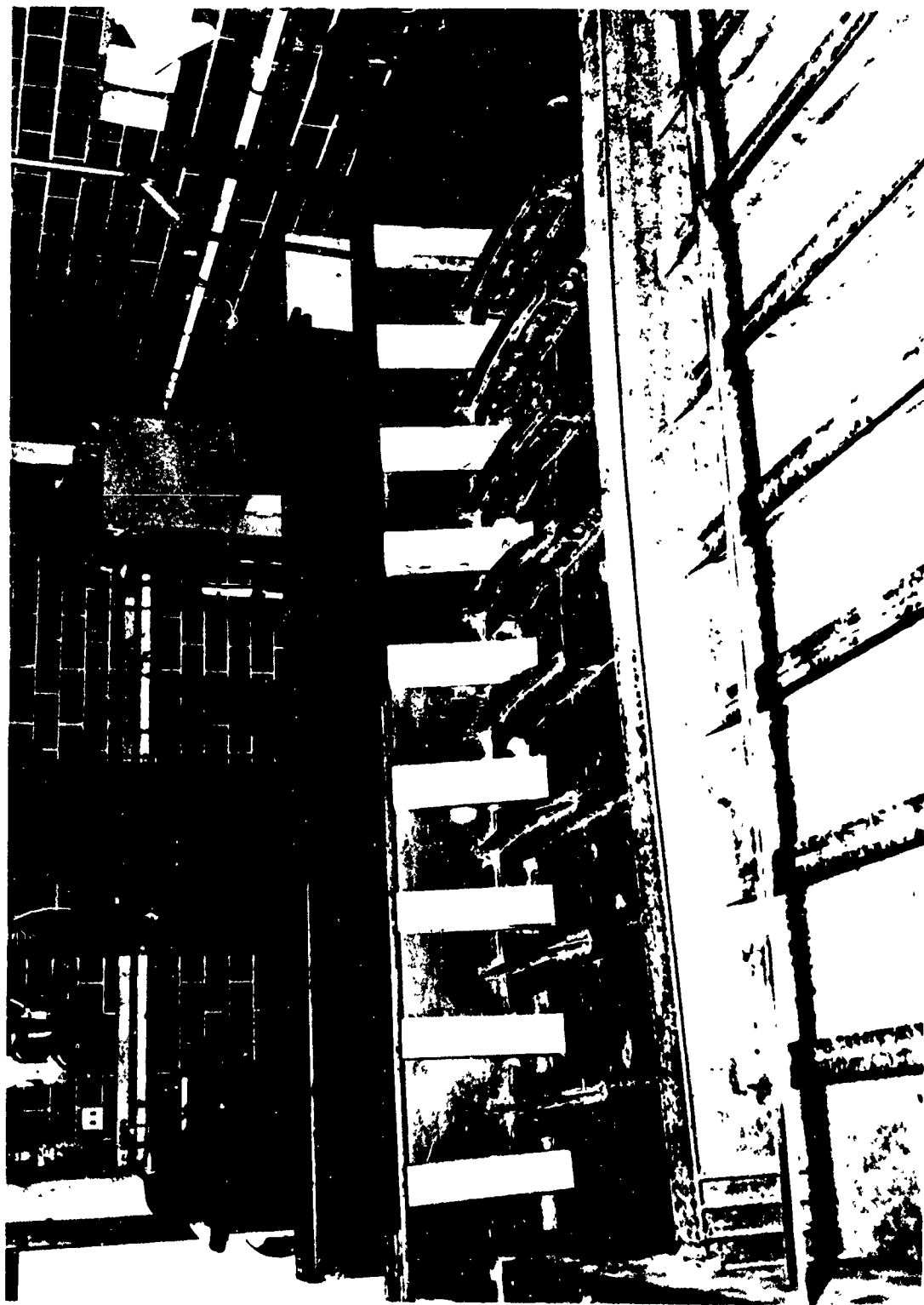
FIGURE 12. CRIPPLING AT THE LOADING END AFTER TEST 1(c)
(NOTE THE CONFIGURATION OF THE END STIFFENER)

FIGURE 13. THE FIXED END, TEST 1(c)

of 34,600 psi, a value above which the axial load could not be maintained.

Examination of the grillage after test showed essentially the same features as in Test 1(b), namely a crippling of the stiffeners at the loaded end. An overall collapse of the grillage did not occur. At least in part, this was because of insufficient torsional rigidity within the heavy I-beam against which the jack pressure is applied. This beam, which is shown in Figure 14, bent and twisted so that the load was no longer applied at the center of gravity of the deformed section.

The lateral deflections recorded are tabulated in Table III.

FIGURE 14. LOADING END AFTER TEST 1(c)

TABLE III

TEST NO. 1(c)

Axial* Pr. (psi)	Lateral Pr. (psi)	Defln** Gage 1 (in)	Defln** Gage 2 (in)	Defln** Gage 3 (in)	Remarks
0	1	0	0	0	
10,100	8	0.4375	0.5000	0.3437	
15,200	8	0.4688	0.5625	0.3750	
20,200	8	0.5000	0.6250	0.3750	
25,000	8	0.5625	0.6563	0.4063	
27,000	8	0.5625	0.6875	0.4063	
30,400	8	0.6250	0.6875	0.4375	
32,400	8	0.6250	0.7188	0.4375	
34,600	8	-	-	-	Axial Pr. Dropped

*Axial pressure on total cross sectional area of 37.125 in^2.

**Gages 1, 2 and 3 were along beam near longitudinal   at first, second and third transversals, respectively, counting from end at which axial lead is applied.

III.   ANALYSIS OF RESULTS

As mentioned in the footnote of Page 10, though extensive strain data were generated in Test 1(a), analysis undertaken herein is confined to that relating to the overall behavior of the grillage under combined axial and normal pressure loads.   Therefore, only a small portion of the data is plotted.

All references in Figures 15 to 24 are, with regard to strain gage location and the designation of stiffeners, according to Figure 6.   The axis "x" is in the longitudinal direction. i.e., parallel to stiffeners, and the axis "y" is at right angles to "x".   Figures 15, 16 and 17 are plots of the ϵ_y strain at the top and bottom surfaces of the plating and Figures 18, 19 and 20 are plots of the ϵ_x strain at the same location.   These strain readings are taken at a transverse section sufficiently far removed from the central transverse stiffener to avoid the local disturbance in stress flow produced by the transverse beam.

It will be seen from Figures 18, 19 and 20 that the longitudinal strain in the plating, ϵ_x, is essentially uniformly distributed at all the combinations of axial force and normal pressure.   The greatest deviations from uniformity are at the highest normal pressure of 15 psi.   Further-more, small and the magnitude does not change appreciably with normal pressure.   It does change, however, with a change in axial pressure.   This shows that: (a) the axial load is carried nearly uniformly by the plating and (b) the bending stresses in the longitudinal direction are small.   These conclusions

FIGURE 15.   STRAIN, ϵ_y, IN THE PLATING 27" FROM THE CENTRAL TRANSVERSAL

FIGURE 16. STRAIN, ϵ_y, IN THE PLATING 27" FROM THE CENTRAL TRANSVERSAL

FIGURE 17.   STRAIN, ϵ_y, IN THE PLATING 27" FROM THE CENTRAL
TRANSVERSAL

FIGURE 18. LONGITUDINAL STRAIN, ϵ_x, IN THE PLATING 27" FROM
THE CENTRAL TRANSVERSAL

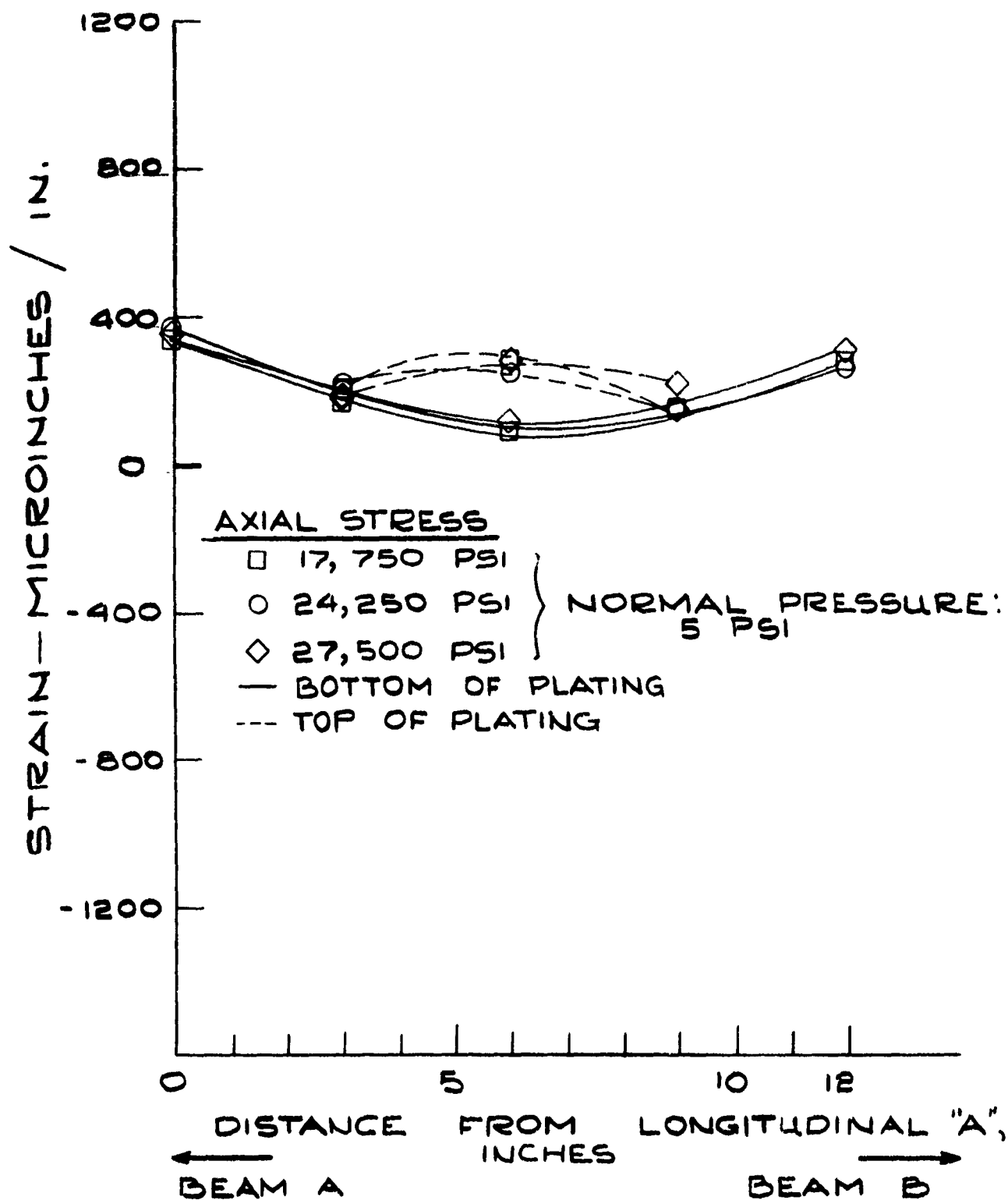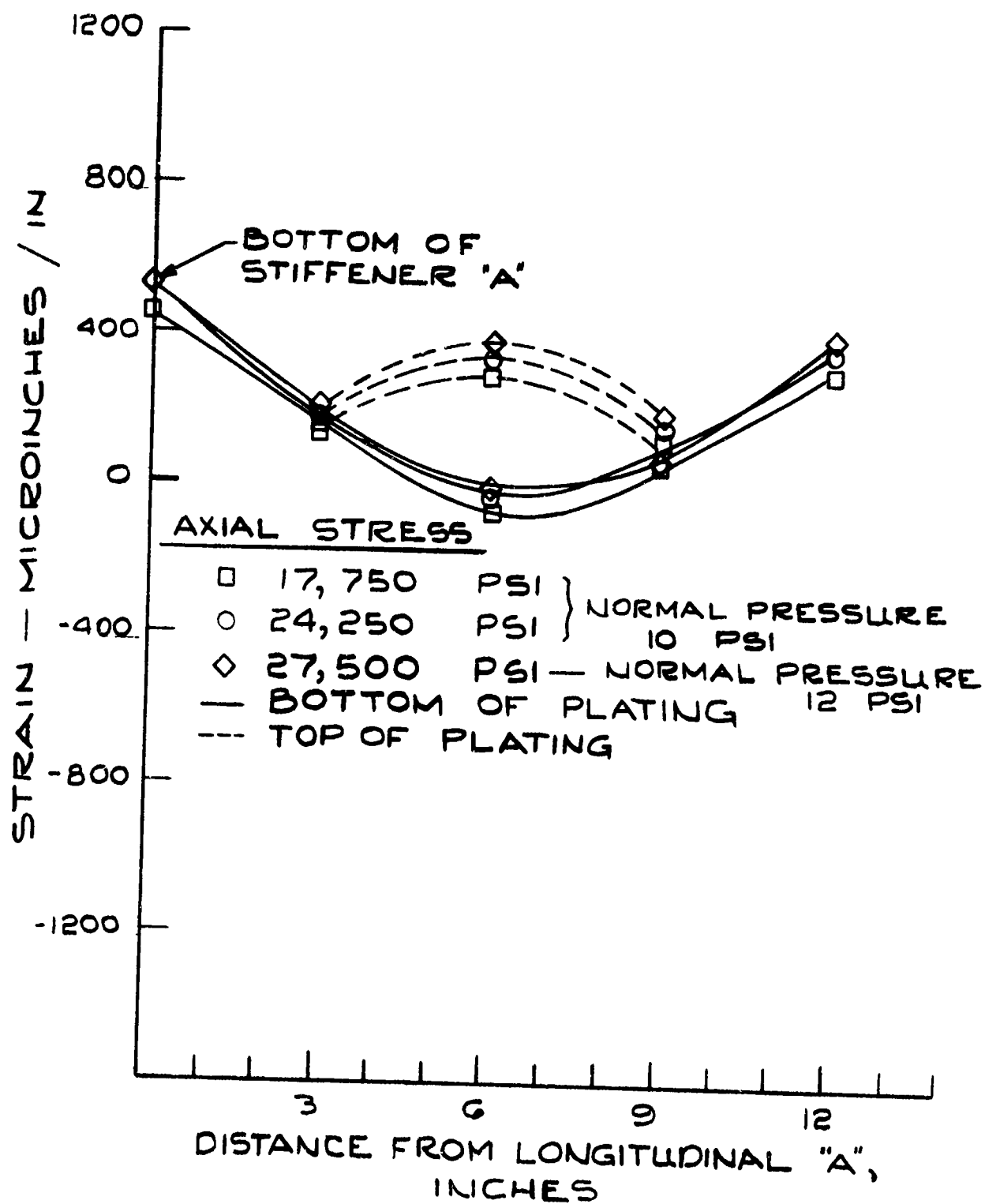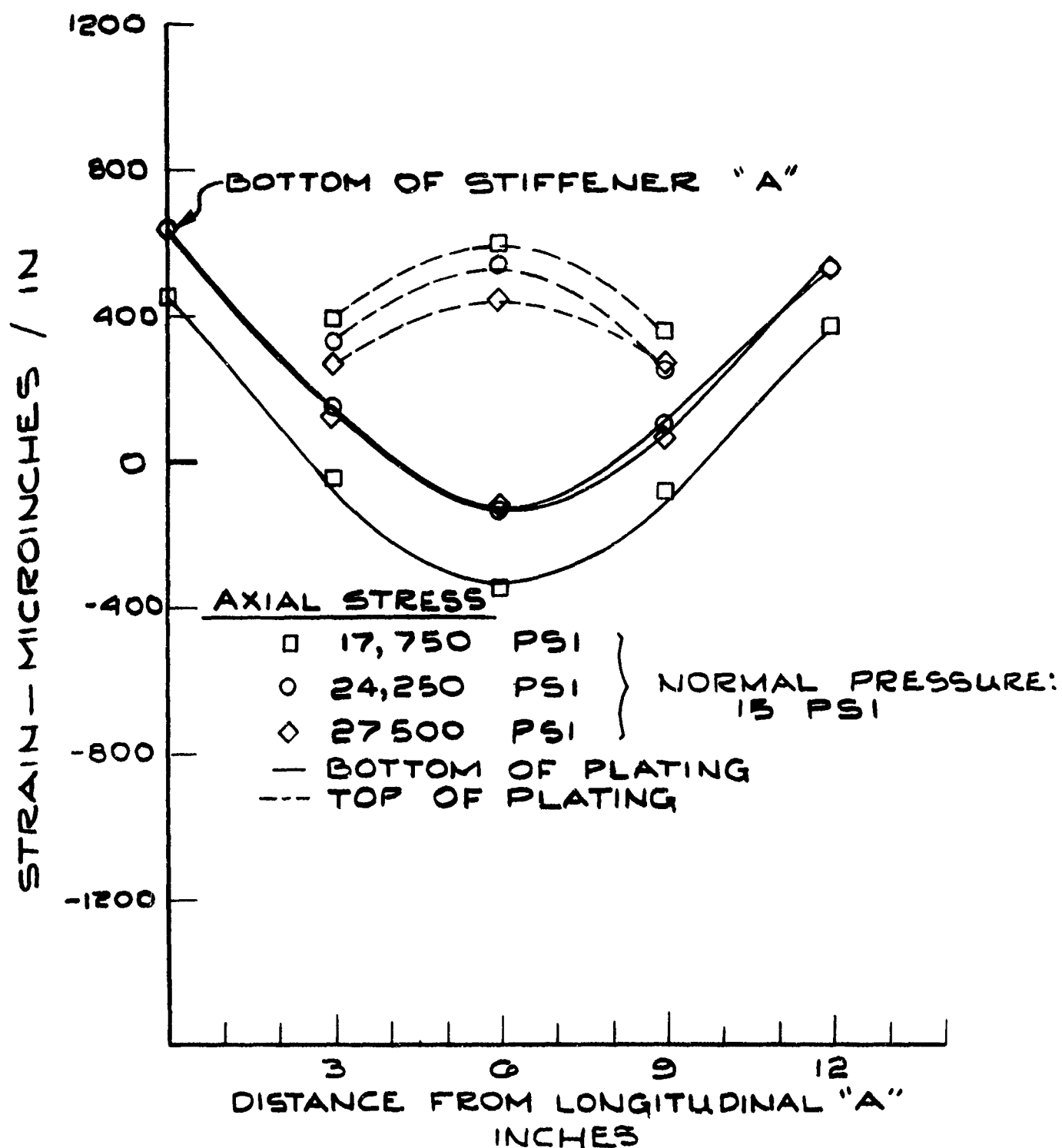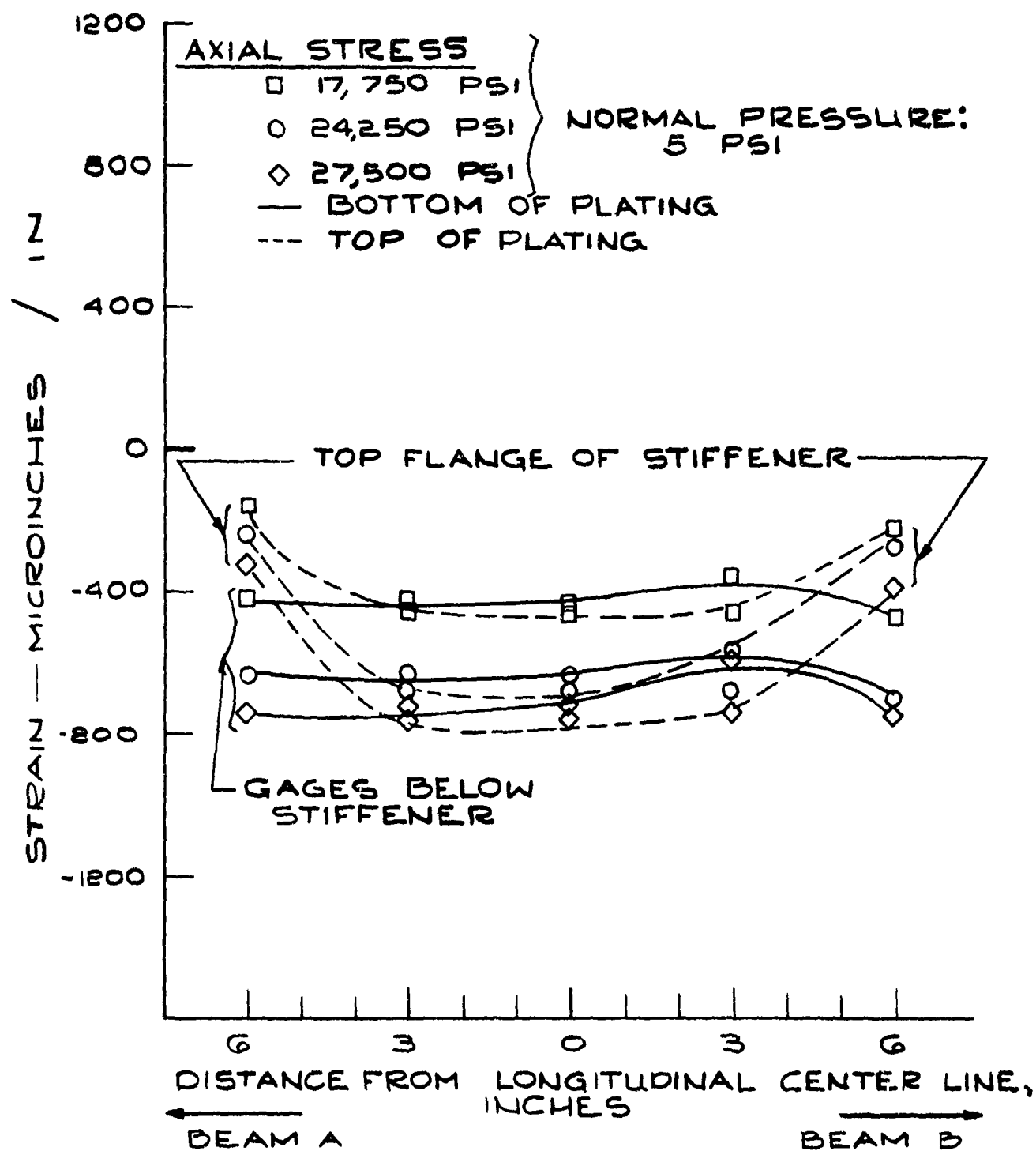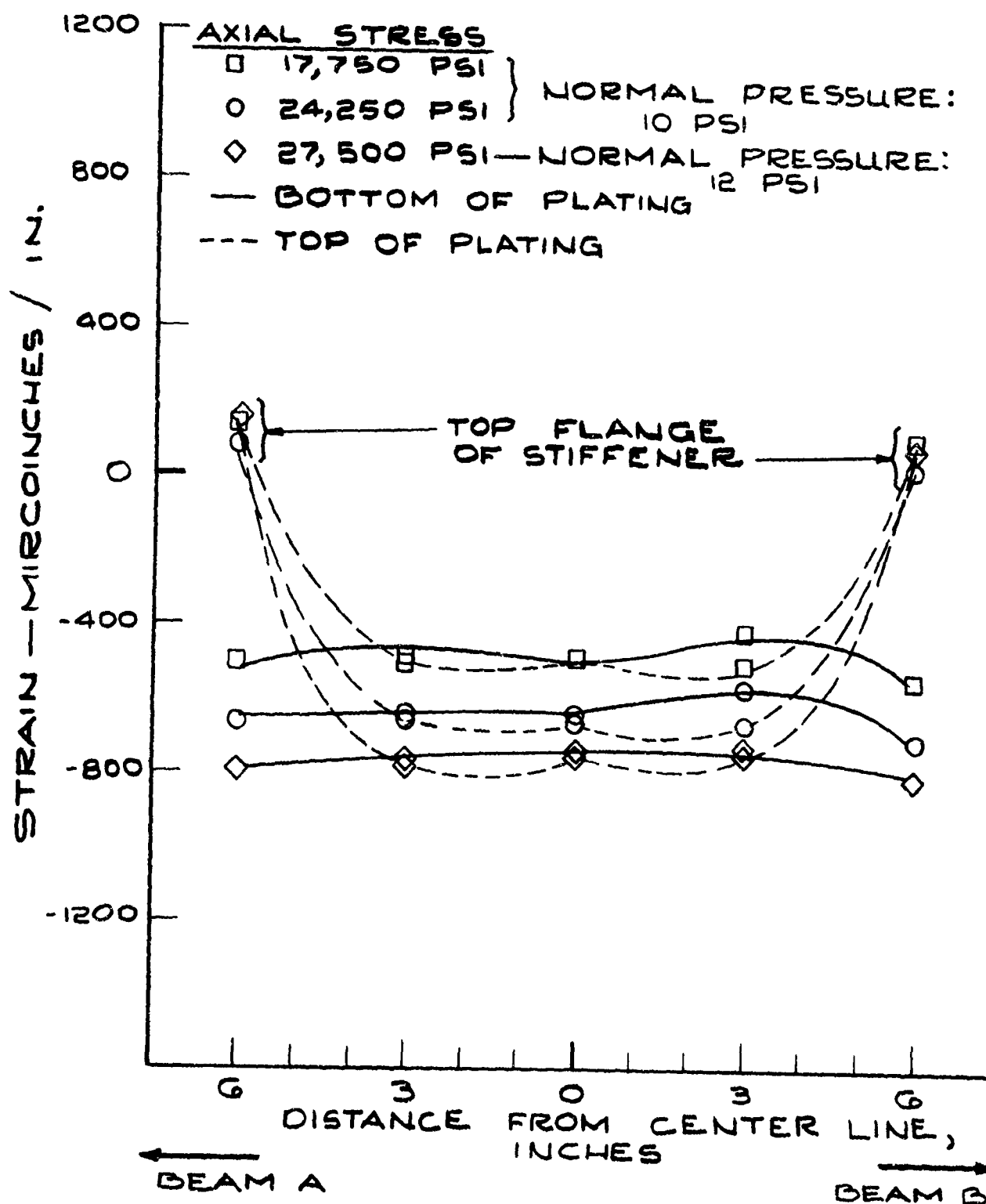FIGURE 19.   LONGITUDINAL STRAIN, ϵ_x, IN THE PLATING 27" FROM
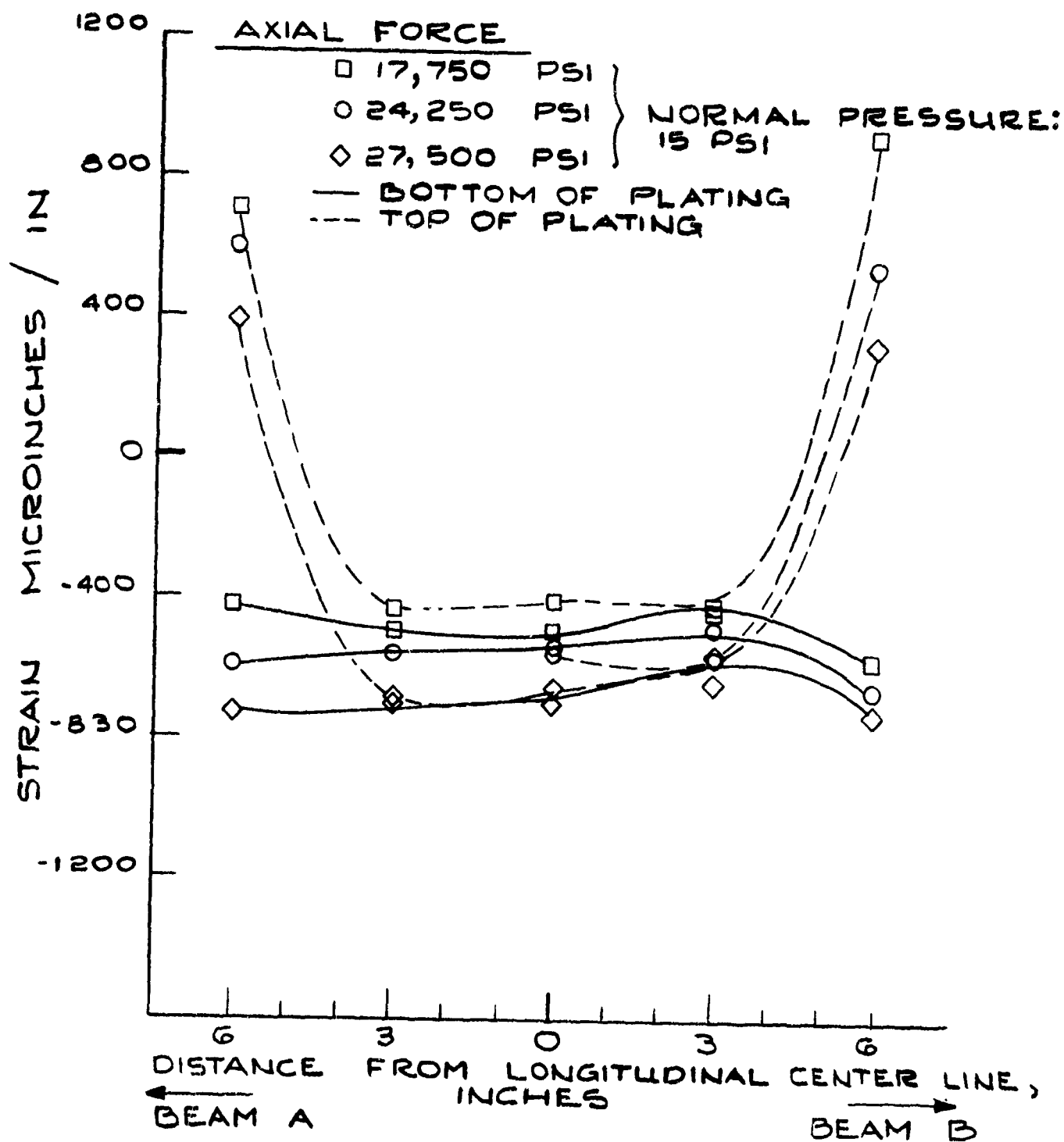THE CENTRAL TRANSVERSAL

FIGURE 20. LONGITUDINAL STRAIN, ϵ_x, IN THE PLATING 27" FROM THE CENTRAL TRANSVERSAL

are in conformity with usual design assumptions, i.e., that because of the panel aspect ratio, the plate undergoes "cylindrical bending."

The foregoing statement is reinforced by examination of Figures 15, 16 and 17 which show plots of the ϵ_y strains in the plating. The strains are always greater on the top surface than on the bottom and, when the pressure is low (5 psi), both sets of strains are positive; in contrast, for the higher pressures, the strains in the bottom become negative and the difference between the strains at the top and the bottom surfaces become greater with increasing normal pressure. These results can be shown to mean that, for the higher normal pressures, the plating bends to a cylindrical surface and at the lower pressures, there is a "membrane tension" in the plating in the transverse direction. This membrane action is reduced at the higher pressures because of the Poisson effect produced by the axial compressive load.

Suppose that the membrane stress, considered uniform, is denoted by σ_y' and the bending stress by σ_y''. Then at the top of the plating:

$$\sigma_y^T = \sigma_y' + \sigma_y'' \tag{1}$$

and, at the bottom of the plating:

$$\sigma_y^B = \sigma_y' - \sigma_y'' \tag{2}$$

Relating stress to strain by Hooke's law:

$$\sigma_y^T = \frac{E}{1-\mu^2} (\epsilon_y^T + \mu \, \epsilon_x^T) \tag{3}$$

$$\sigma_y^B = \frac{E}{1-\mu^2} (\epsilon_y^B + \mu \, \epsilon_y^B) \tag{4}$$

From Equations (1), (2), (3) and (4), the membrane and bending stresses, σ_y' and σ_y'', may be written in terms of strains, viz.:

$$\sigma_y' = \frac{E}{2(1-\mu^2)} \left\{ \epsilon_y^T + \epsilon_y^B + \mu \ (\epsilon_x^T + \epsilon_x^B) \right\} \tag{5}$$

$$\sigma_y'' = \frac{E}{2(1-\mu^2)} \left\{ \epsilon_y^T - \epsilon_y^B + \mu \ (\epsilon_x^T - \epsilon_x^B) \right\} \tag{6}$$

Consider Equation (5) which gives the membrane stress σ_y'. At 5 psi, Figure 14 shows that both ϵ_y^T and ϵ_y^B are positive; then from Figure 18, ϵ_x^T and ϵ_x^B are both negative. Thus, the membrane stress has a positive value for small pressures. As the normal pressure increases, however, ϵ_y^B becomes negative (see Figures 16 and 17); therefore, although $\epsilon_y^T + \epsilon_y^B$ still remain positive, the effect of the negative value of $\mu(\epsilon_x^T + \epsilon_x^B)$ reduces the value of σ_y'. Also, this reduction increases for greater values of the axial compressive stress. As an example, at 5 psi normal pressure and 17,750 psi axial stress:

$$\epsilon_y^T = 240 \text{ and } \epsilon_y^B = 100; \text{ also, } \epsilon_x^T = -460 \text{ and } \epsilon_x^B = -430$$

At 5 psi normal pressure and 27,500 psi axial stress:

$$\epsilon_y^T = 280 \text{ and } \epsilon_y^B = 120; \text{ also, } \epsilon_x^T = -760 \text{ and } \epsilon_x^B = -720$$

And at 15 psi normal pressure and 27,500 psi axial stress:

$$\epsilon_y^T = 440 \text{ and } \epsilon_y^B = -120; \text{ also, } \epsilon_x^T = -660 \text{ and } \epsilon_x^B = -700$$

All strains are in microinches per inch and are measured at the center of the panel. Using Equations (5) and (6) and, assuming $E = 29 \times 10^6$ psi and $\mu = 0.3$, we get the following results:

At 5 psi normal pressure and 17,750 psi axial stress:

Membrane stress $\sigma_y' = 1160$ psi

Bending stress $\sigma_y'' = \pm 2090$ psi

At 5 psi normal pressure and 27,500 psi axial stress:

Membrane stress $\sigma_y' = -700$ psi

Bending stress $\sigma_y'' = \pm 2360$ psi

At 15 psi normal pressure and 27,500 psi axial stress:

Membrane stress $\sigma_y' = -1400$ psi

Bending stress $\sigma_y'' = \pm 9100$ psi

These values are, of course, approximate and are based on the assumption of uniform distribution of membrane stress. They serve to show that as the axial load increases, the "membrane effect" is reduced and, in fact, may reverse in sign. The bending stress increases with normal pressure, as expected and as may be seen from Equation (6), with the quantity $(\epsilon_y^T - \epsilon_y^B)$ because $(\epsilon_x^T - \epsilon_x^B) \approx 0$ in most cases. Thus, the bending of the plate is primarily a function of normal pressure and is relatively unaffected by axial load.

Figure 21 shows the strains in the longitudinal stiffener A at an axial compressive stress of 17,750 psi and various normal pressures. It may be noted that the strain distribution, while nonlinear at the lower pressures, approaches linearity at the highest normal pressure of 15 psi. The interesting feature is that, as the normal pressure increases, there is very little change in the bottom flange strain. This is not only because of the cylindrical bending of the panels previously noted but, also, because the "bottom flange" actually consists of an effective width of plating which
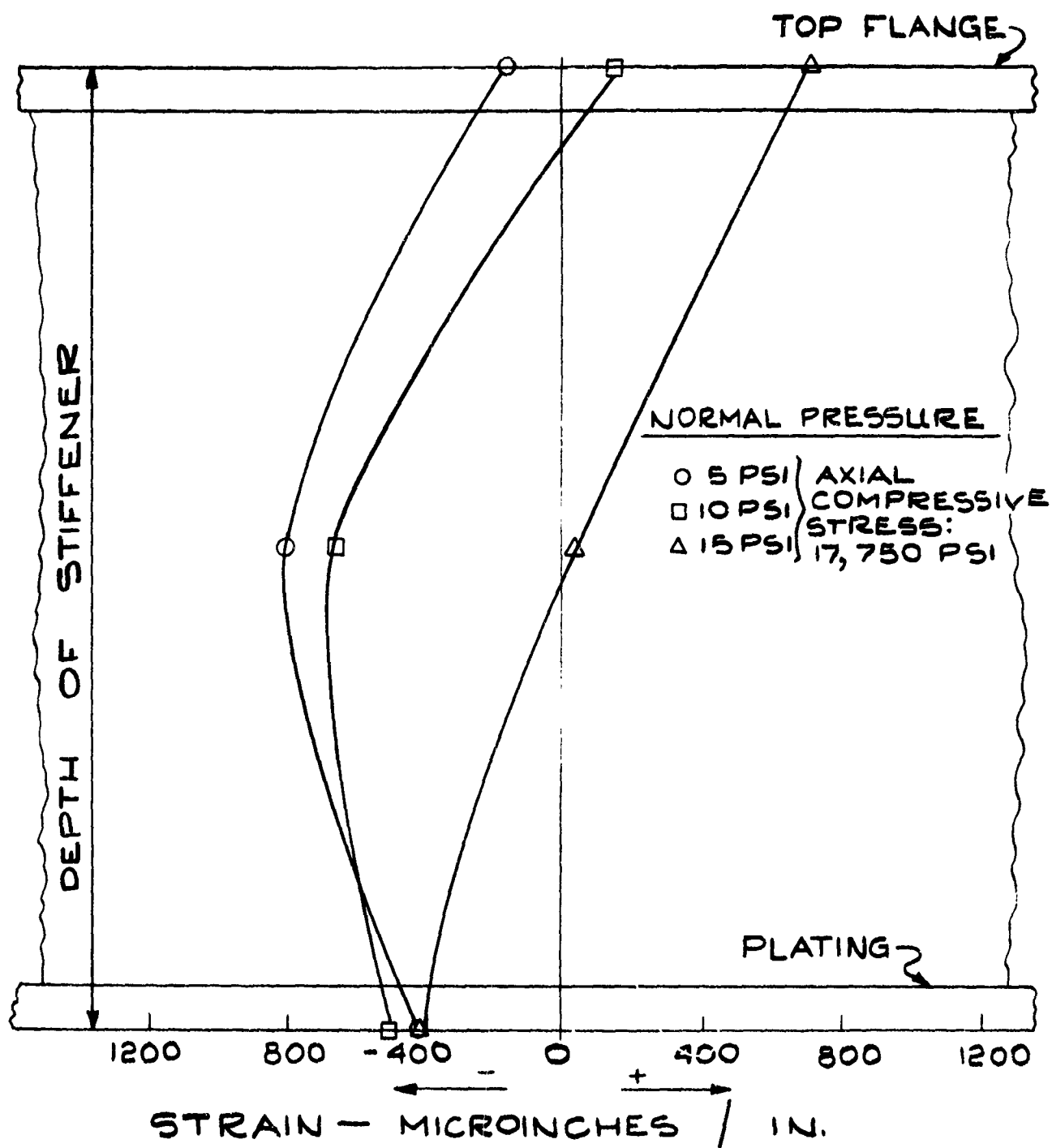
FIGURE 21. LONGITUDINAL STRAIN, ϵ_x, IN THE LONGITUDINAL "A"
27" FROM THE CENTRAL TRANSVERSAL

provides a measure of lateral restraint. In contrast, the top flange strains change noticeably and the compressive strain in the web decreases rapidly with the increase of pressure.

Figure 22(a) gives the strain distribution in the grillage longitudinals at the axial stress of 24,250 psi. It will be noted that the strains in the top flange of the longitudinal have changed little from their corresponding values in Figure 21. The strains in the "bottom flange," however, have increased noticeably. Again, at the maximum pressure of 15 psi the strain distribution is linear (almost perfectly linear in this case), with the geometric center of the section experiencing zero strain.

These features lead to certain interesting conclusions. For instance, since the top flange strains increase with normal pressure and have virtually the same values at the axial stresses of 17,750 psi and 24,250 psi, we may conclude that, as the axial load is increased, the axial compression is no longer transferred to the top flange, and is therefore less uniformly distributed. Also, since the axial compressive strain in the bottom plating increases with increase of axial load, we may conclude that a proportionately greater part of the stress is transferred to the bottom plating.

However, as the normal pressure is increased, the strain distribution becomes nearly linear, approaching, approximately, the ideal case of zero axial pressure. This phenomenon may be explained by the hypothesis that with increase of normal pressure, the axial load tends to be taken by the longitudinal boundaries of the grillage which are relatively rigid.

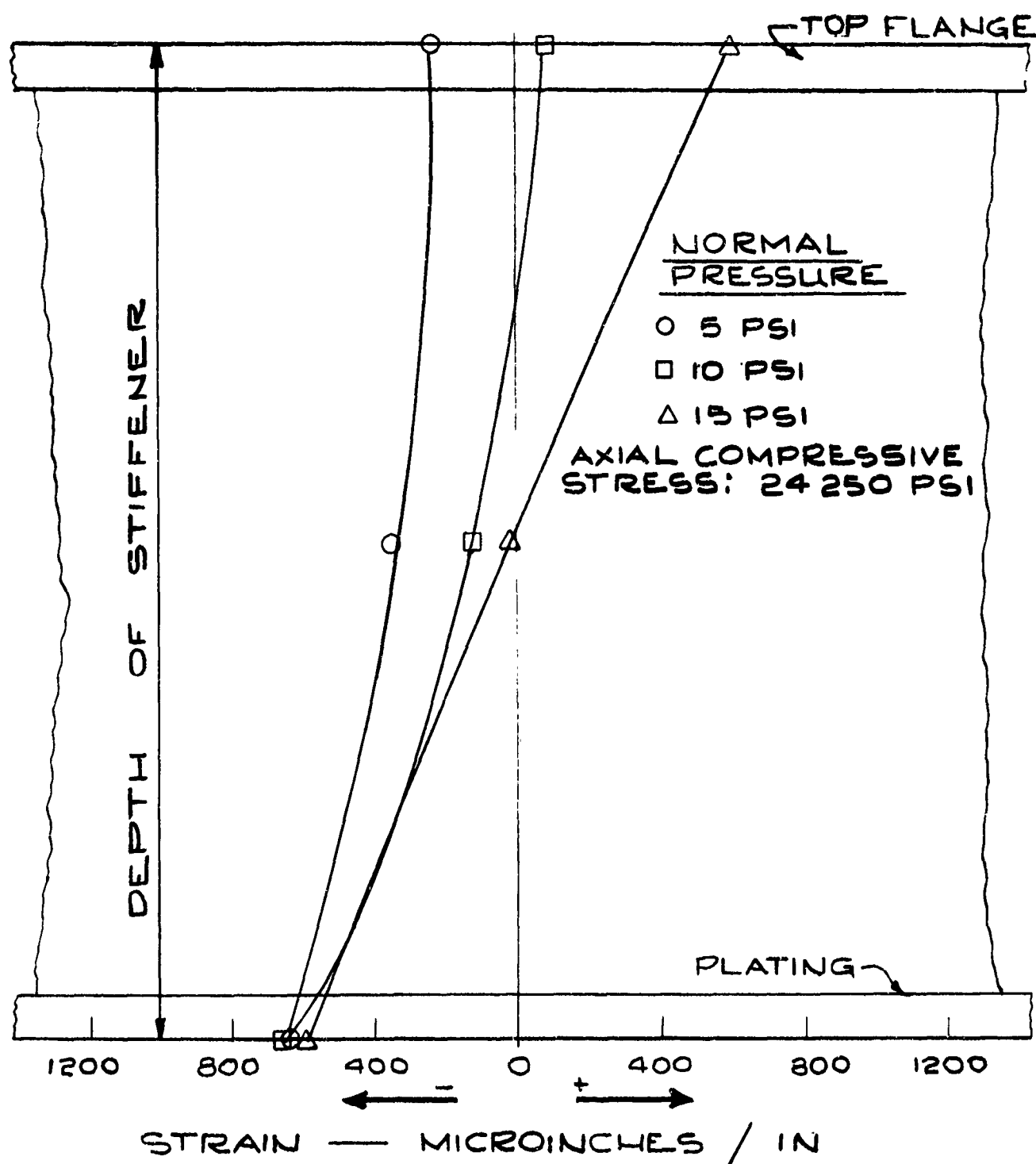The stress in the bottom plating is given by:

FIGURE 22(a). LONGITUDINAL STRAIN, ϵ_x, IN THE LONGITUDINAL "A"
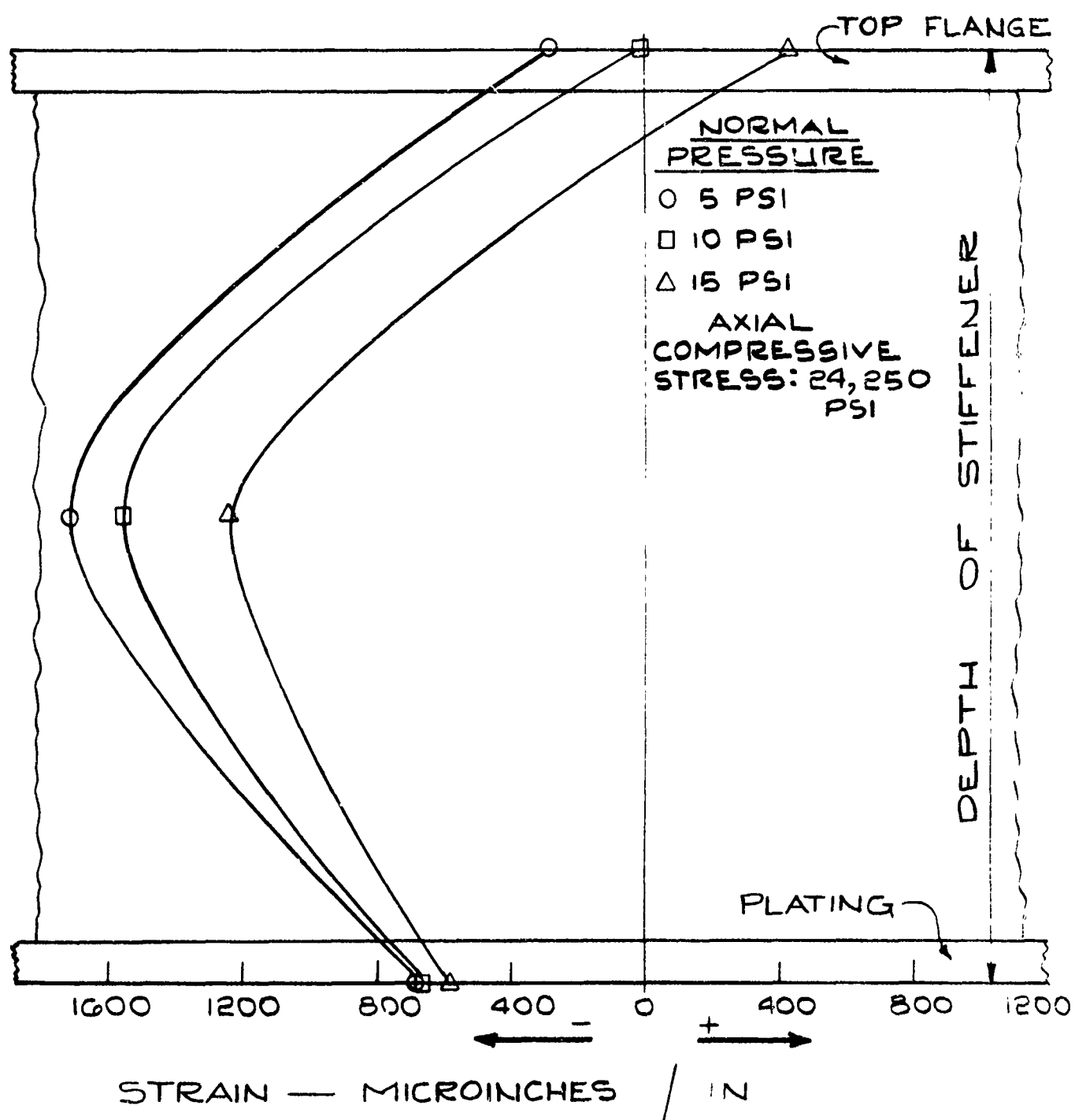27" FROM THE CENTRAL TRANSVERSAL

FIGURE 22(b).   LONGITUDINAL STRAIN, ϵ_x, IN LONGITUDINAL "A"
18" FROM THE CENTRAL TRANSVERSAL

$$\sigma_x = \frac{E}{1 - \mu^2} (\epsilon_x + \mu \ \epsilon_y)$$

Figures 15, 16 and 17 show that ϵ_y increases with normal pressure. This is to be expected because the plate has a strong curvature at the longitudinal stiffeners and the symmetry of the structure prevents rotation of the longitudinals; the panel, therefore, acts like a "fixed ended" plate. ϵ_x, on the other hand, is practically unaffected by the normal pressure and as the preceding equation shows, as normal pressure is increased, σ_x in the plating is reduced. Since the total axial load does not change with increasing normal pressure, this can only mean that part of the axial load is transferred to the boundaries. This is very similar to the "effective width" phenomenon, long recognized in the post buckling behavior of plating. Therein, it has been found that the nature of the boundaries always plays an important part in the mechanisms of failure and must, therefore, be taken into account in an ensuing analysis.

In summary, the conclusions are two-fold, viz., (a) as the axial load is increased, the bottom plating carries the bulk of the increase and (b) as the normal pressure is increased, the axial load tends to be transferred to the boundaries of the grillage.

The strains at various sections along the central transverse stiffener are given in Figures 23 and 24. Strains 7 inches from the side of the grillage could not be plotted with any accuracy because, apparently, there was considerable strain concentration at this section and the resultant strain records were unsatisfactory.

It will be noted that both at 17,750 psi and 24,250 psi axial stress, the strain distribution was nearly linear 27 inches from side of grillage
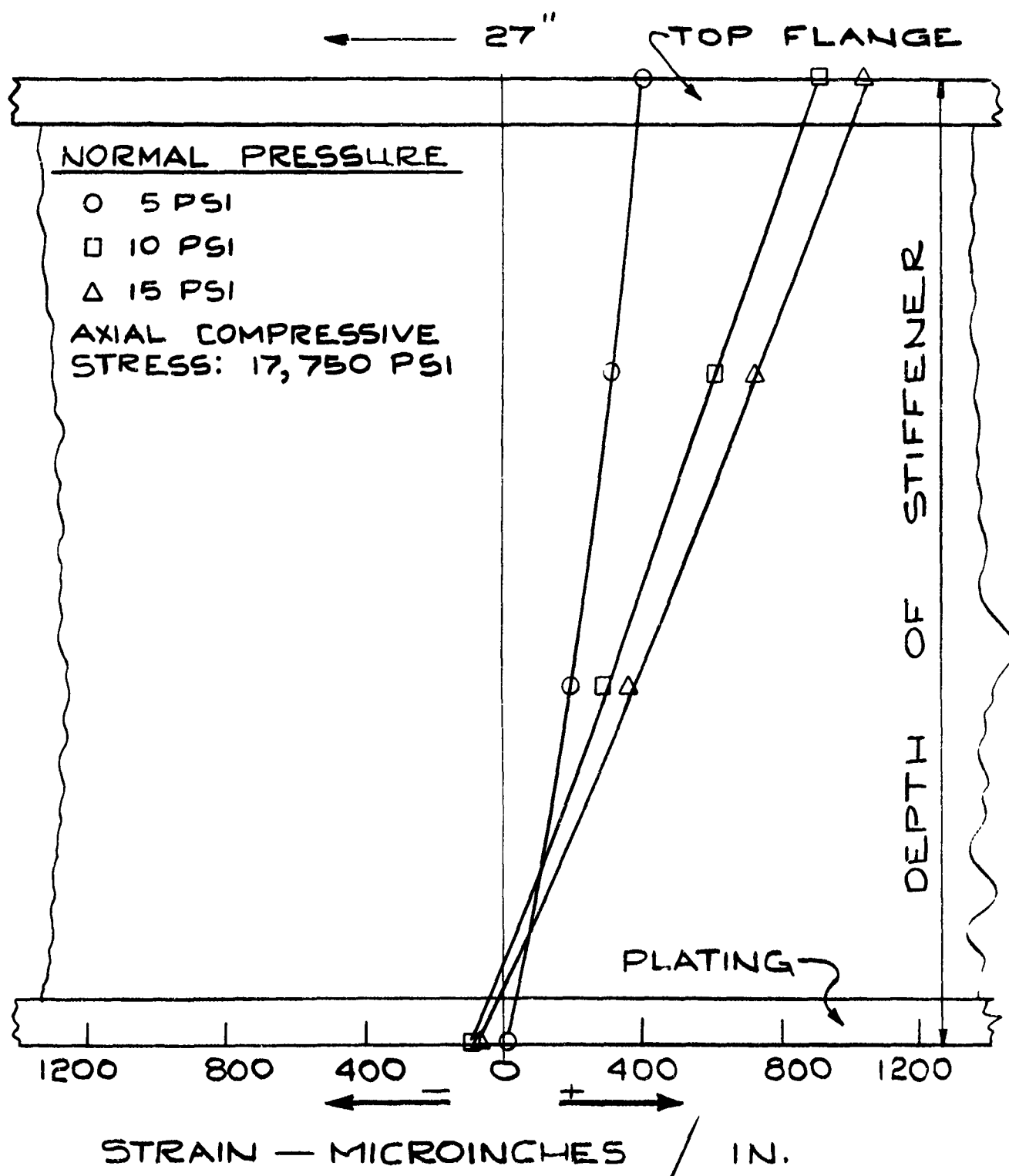
FIGURE 23(a).   STRAIN IN THE CENTRAL TRANSVERSAL 27" FROM
THE GRILLAGE EDGE
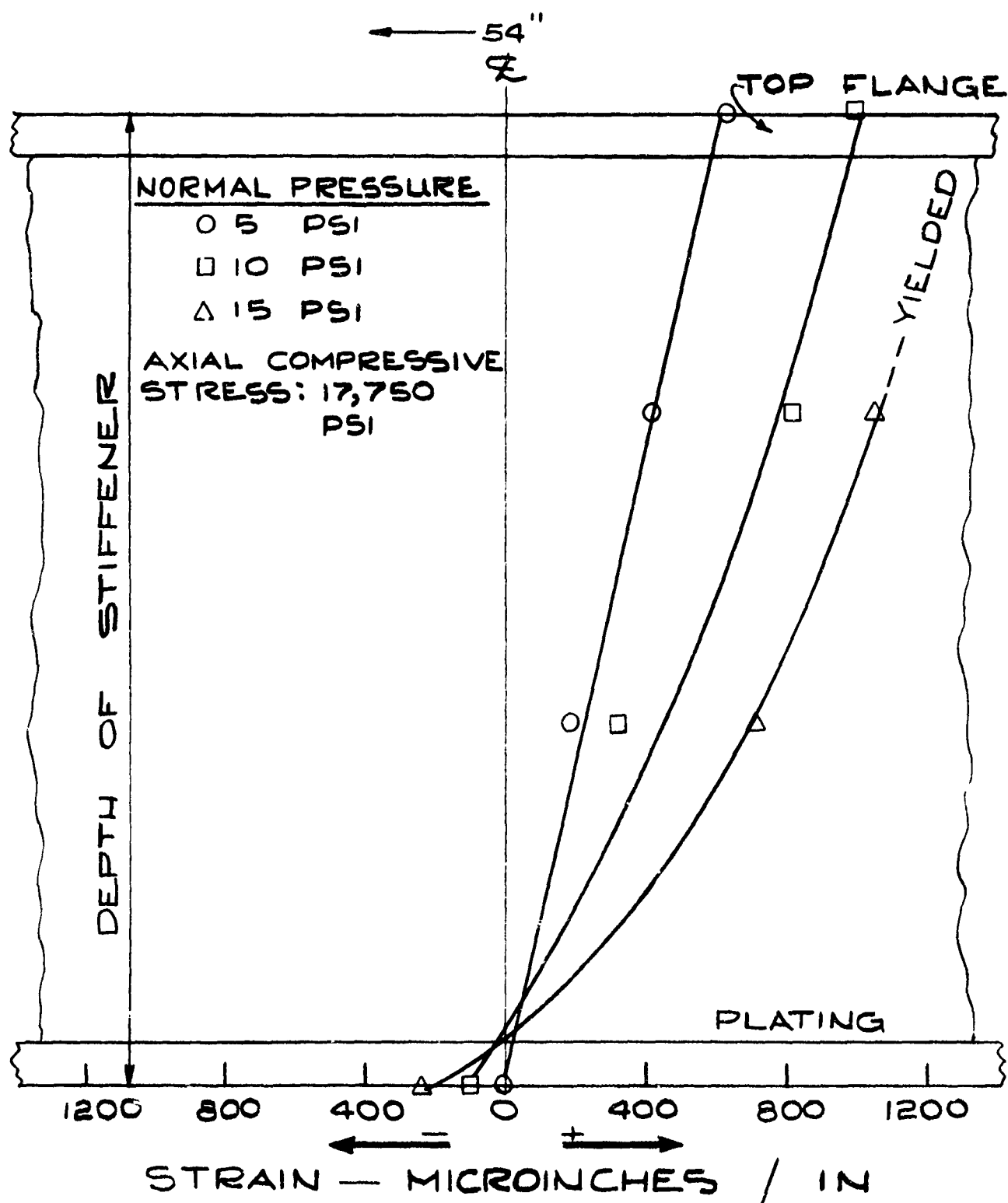
FIGURE 23(b). STRAIN IN THE CENTRAL TRANSVERSAL AT THE GRILLAGE CENTERLINE
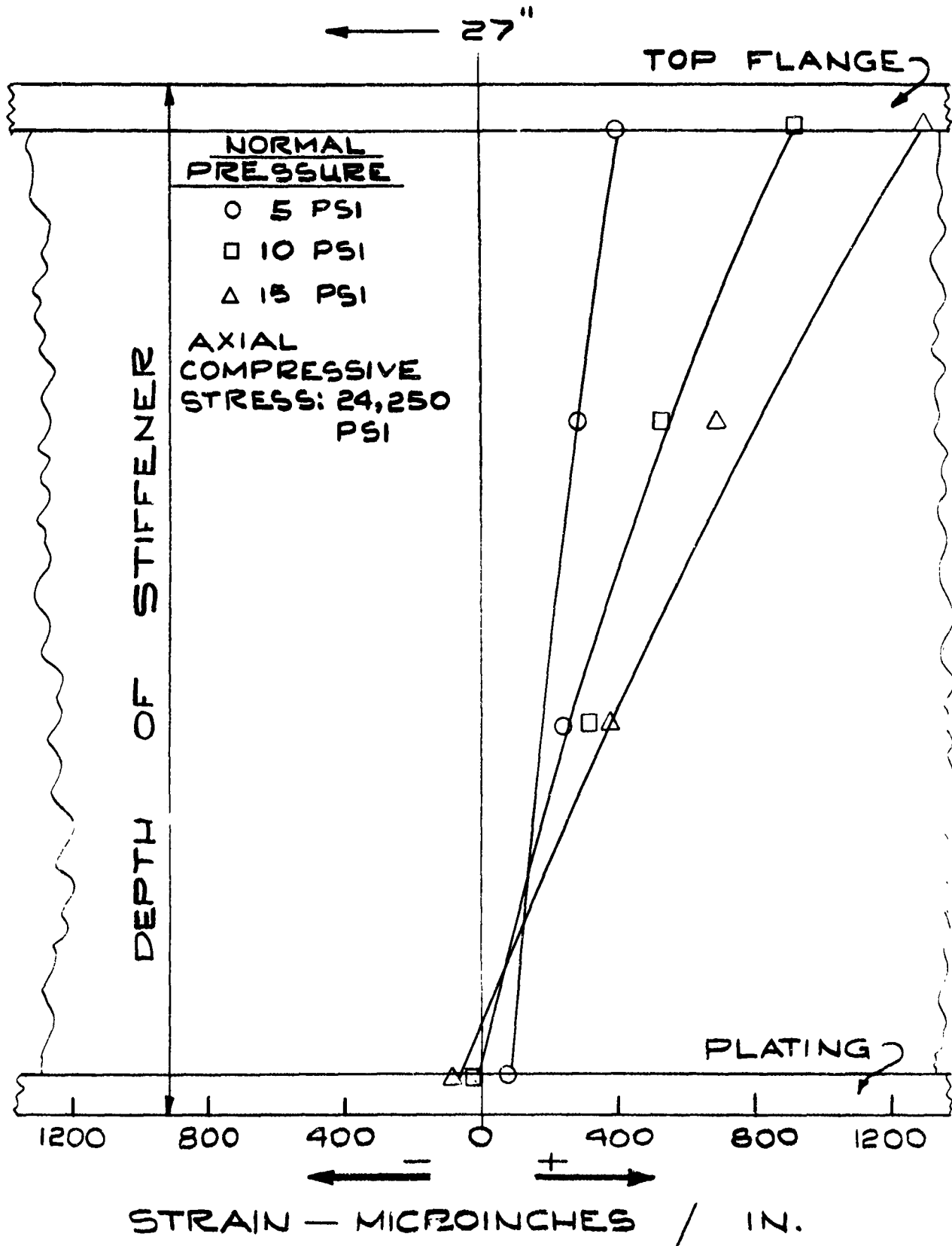
FIGURE 24(a).   STRAINS IN THE CENTRAL TRANSVERSAL 27" FROM
THE GRILLAGE EDGE
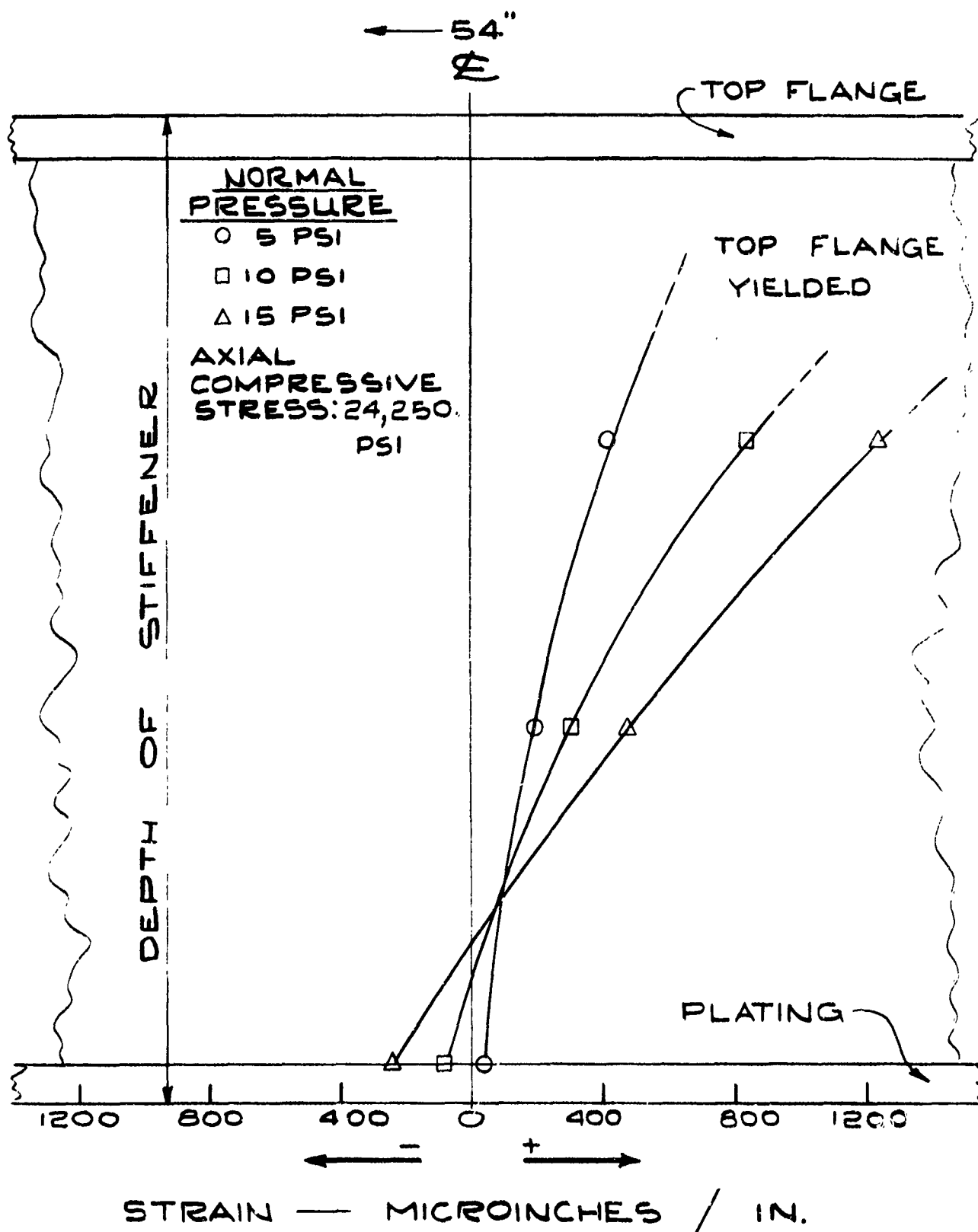
FIGURE 24(b).   STRAINS IN THE CENTRAL TRANSVE...AL AT THE
GRILLAGE CENTERLINE

and, at low pressures, this linearily was maintained to the longitudinal centerline of the grillage. Moreover, at all pressures, the zero strain axis is close to the bottom plating. This shows that the effective width of plating is virtually unaffected by either the axial load or the normal pressure. Thus, the behavior of transversals, because of the absence of axial loads, is quite different from that of the longitudinals.

IV.   CONCLUSIONS

In summary, analysis of the data leads to the following general
interrelated conclusions, most of which tend to confirm the assumptions
usually made for grillage design.   These are:

1)   The axial load is carried principally by the grillage

plating.   The resultant compressive stress is fairly

uniform, particularly at low axial loads, and longitudinal

bending induced by axial load is small.

2)   Bending stress in the grillage is primarily a function of

normal pressure.   At low normal pressures, i.e., 5-10

psi in the case of the grillage tested, a transverse mem-

brane tension resulting from edge clamping restraint is

evident.   This effect does not increase in direct proportion

as normal pressure is increased because of the Poisson

effect induced by the axial compression.

3)   As the normal pressure is increased from, say 10 psi in

the case of the grillage tested, a greater portion of the

axial load is transferred to the relatively rigid side

boundaries.

4)   For the transverse beams the effective width of plating is

virtually unaffected by either axial load or normal pressure.

In addition to the above conclusions which concern the actual

behavior of the tested grillage, it is also to be mentioned that - in retro-

spect - certain changes in specimen geometry, in test instrumentation and test procedure and in design of the test hardware would yield other information of considerable value in grillage design methods. In particular, it must be noted that the manner in which the axial load is introduced into the grillage is of paramount importance to the specimen failure mode. As previously mentioned, failure in the grillage tested was via local crippling at the load end; therefore, the true ultimate strength of the grillage was not determined.

A discussion regarding desireable modifications which should be made in the event of future tests follows in Appendix A of this report.

APPENDIX A

OUTLINE OF A RECOMMENDED PROGRAM

Outlined in the pages following is a program designed to comple-
ment the effort described in the preceding sections by means of further
tests performed on grillages slowly loaded from initial elastic conditions
until final plastic collapse. The program objective is not merely to
ascertain collapse conditions, but, also, to learn enough about the struc-
tural response so that analytical predictions for other grillages operating
under similar conditions will be possible. It is necessary, therefore, to
devote considerable attention to the analysis of test results at every stage,
starting first with strain data from the better-understood elastic range,
then continuing on into the elasto-plastic range. By so doing, it will be
possible to convert strains in the elastic range to stresses and thereby
calculate resisting moment, effective width, etc., in order to form a
conceptual understanding of the grillage behavior. Once plastic behavior
is initiated (and, in the grillage this will no doubt occur simultaneously
at several sections), strains cannot easily be converted to stresses and
it will then be necessary to develop a reasonable hypothesis regarding the
grillage behavior. Such a hypothesis will not be precise in all details but
will, nevertheless, allow prediction of the grillage response close to its
final collapse load. The elastic stage information will be useful, apart
from its own intrinsic value, mainly in serving as a guide to the likely
behavior in the later elasto-plastic stage. In this regard, it should be

remembered that the grillage will never become completely plastic throughout the conditions of the test. Much of the plating will remain elastic and, quite probably, large portions of the stiffening beams also. However, the grillage will become plastic at several critical points and its remaining capacity for taking additional load will drop in dramatic fashion.

Thus, it would seem necessary to concentrate attention at those sections of the grillage which are likely to be critical in determining "collapse." In the case of purely lateral loads, the critical sections are at the intersections of the stiffeners which, theoretically, form "plastic hinges." Although the behavior may be different in the case of both axial and lateral load, it is believed that behavior at the intersection points or "nodes" will still be of importance in determining collapse. Nevertheless, since the grillage has plating, the behavior of the beams between nodes cannot be wholly disregarded, especially when the geometric center of the grillage is not also a node.

The foregoing discussion is intended to show, first, that by choice of critical locations, it is possible to reduce the number of strain gages from that employed in the test reported in this document and, secondly, that the study of the elastic stage must precede loading of the grillage into the plastic range. It is to be recalled that, in the tests discussed herein, that certain combinations (Data Points) of axial and lateral loads were used; therefore, there was no guarantee that certain sections of the

grillage had not already yielded during test at a prior Data Point. Also, when both axial and lateral loads were varied, the analysis of strain data became quite difficult.

For these reasons, then, a program as outlined below appears to have merit:

(a)   A modification of the test facility - This modification is of a minor nature, involving only additional torsional stiffness and bending strength for the transverse I-beam at the loading end of the loading frame. Previous tests showed that, at large axial loads and normal pressures, the beam was bent out of plane and, also, twisted; this resulted in an eccentricity of the applied load.

(b)   Test three new grillages of different proportions - One of the major difficulties in the previous tests was associated with local crippling of the grillage specimen, particularly at the loading end. This feature of the behavior of the grillage is now well understood and the manner in which the load should be transferred into the grillage is apparent.

As has already been mentioned, it is desireable to obtain strain data in the purely elastic stage of the grillage before loading into the plastic state. For this purpose, a combination of small axial loads and normal pressures are necessary. The procedure, therefore, should be to maintain the axial load constant and increase the normal pressure in steps of, say, two psi up to about ten psi. then unload the grillage com-

pletely. The derived data should then be analyzed to determine bending moments, and effective width of plating in each direction. Next, a lateral load of about ten or fifteen psi should be applied and the axial load increased in steps until collapse occurs.

From the strain data in the elastic stage and, also, from this information gained in the subsequent loading into the plastic range, an analytical procedure should be developed for predicting the deflections of the elastic-plastic grillage as well as its final collapse load.

Of the three tests proposed, the first two should carry a fairly large number of strain gages and tested similarly. In addition, the third and last test should carry a minimum of instrumentation at locations dependent upon the results of the first two. The main purpose of this test would be to verify the analysis methods, particularly as regards to prediction of the grillage behavior in the plastic range.

As to specific configuration and instrumentation for the proposed tests, it is to be kept in mind that, in the first two tests, the major emphasis would be on data acquisition and theoretical analysis while in the last test, the emphasis should shift to verification and confirmation. The first two specimens, therefore, would not be radically different from that previously tested; the third, however, would be decidedly heavier and, thus, becomes the medium for checking analytical procedures developed on the basis of Specimens 2 and 3 test results. Suggested sections are as given below, starting with the designation "Specimen 2 ' to differentiate from the previous tests which may be called "Specimen 1. "

(a)   Specimen No. 2

Tra..sversals: 10 x 4 x 17# Light Beams Cut to Tees,

Spacing 54", 3 Stiffeners, 4 Bays

Longitudinals: 3 x 2.2# Tees, 12" Spacing, 8 Longitudinals

Plating: 1/4" in Thickness

(b)   Specimen No. 3

Transversals: 10 x 4 x 17# Light Beams Cut to Tees,

Spacing 54", 3 Stiffeners, 4 Bays

Longitudinals: Same as in Specimen 2, but 18" Apart,

5 Longitudinals

Plating: 1/4" in Thickness

(c)   Specimen No. 4

Transversals: 12 x 4 x 22# Light Beams Cut to Tees,

Spacing 54", 3 Stiffeners, 4 Bays

Longitudinals: 6 x 4 x 16# Light Beams Cut to Tees,

Spacing 12", 8 Longitudinals

Plating: 1/2" in Thickness

All material would be mild steel.

The proposed instrumentation for Specimen No. 2 is given in

Figure 25 wherein, it will be noted that the total number of suggested

strain gages is 144. Although this represents a considerable reduction

from that used in Test No. 1 of this report, the number is felt to be quite

sufficient. For Specimen No. 3 the instrumentation would be similar to

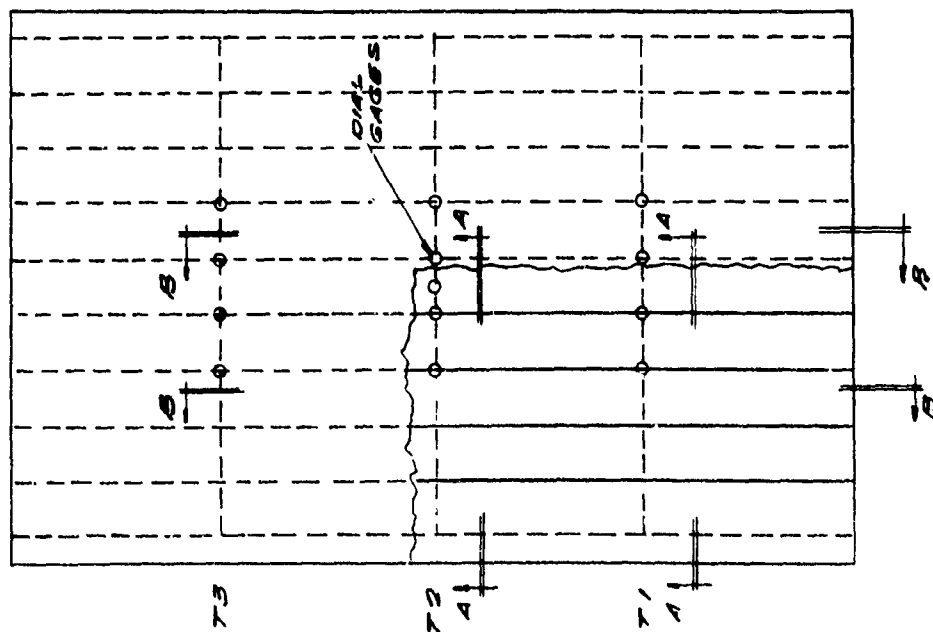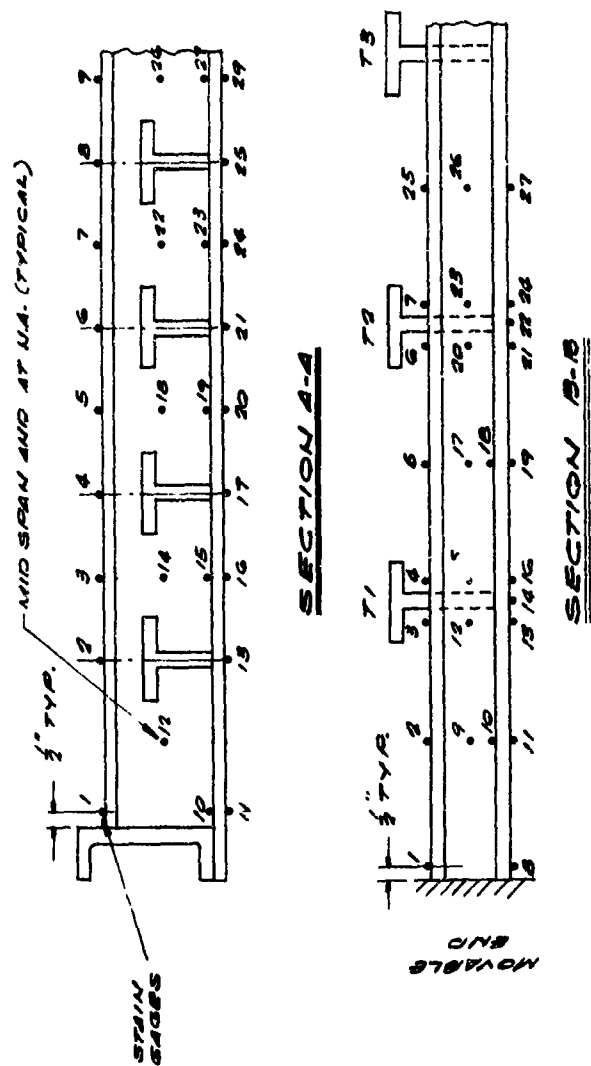that in Specimen No. 2 but the total number of strain gages would be

FIGURE 25(a). INSTRUMENTATION PLAN FOR PROPOSED SPECIMENS 2, 3 AND 4

FIGURE 25(b).   STRAIN GAGE KEY

Transversals 1 and 2		Longitudinal		
			A	B
Location	Gage Type	Location	Gage Type	
1	U	1	U	-
2	U	2	U	-
3	U	3	U	-
4	U	4	U	-
5	U	5	U	U
6	U	6	U	-
7	U	7	U	-
8	U	8	U	-
9	U	9	B	-
10	U	10	U	-
11	U	11	B	-
12	T	12	T	-
13	B	13	U	-
14	T	14	B	-
15	U	15	T	-
16	U	16	U	-
17	B	17	B	-
18	T	18	B	-
19	U	19	B	B
20	U	20	T	B
21	B	21	U	U
22	T	22	B	B
23	U	23	T	B
24	U	24	U	U
25	B	25	U	U
26	T	26	B	-
27	B	27	B	-
28	B			

Notes: (1)   For Specimen 2, instrument Transversals 1 and 2 and
Longitudinals A and B.   Total number of gages: 144.

(2)   For Specimen 3, instrument Transversal 1 only and
Longitudinals A and B.   Total number of gages: 100.

(3)   For Specimen 4, limit number of gages to 48; locations to
be determined on the basis of Specimens 2 and 3 results.

(4)   Designation: U is a uniaxial gage, B is a biaxial rosette,
and T is a triaxial rosette.

reduced to 100. This would be accomplished by dropping out the gages on the Transversal No. 1, see Figure 25. Specimen No. 4 would be instrumented with a maximum of 48 strain gages at, as previously mentioned, locations dependent upon the results of Specimens 2 and 3.

It is felt that the above program would materially add to the tests described in this report and, in addition, lead to a more thorough understanding of the grillage problem as a whole.

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13 ABSTRACT

This report is concerned with an experimental evaluation of the behavior of plated grillages under the simultaneous action of a uniform normal pressure and axial compression. The combination of loads was gradually increased so as to produce large plastic deformation, the aim being to obtain an estimate of the collapse strength of the grillage.

The test procedure is described and conclusions are drawn regarding the behavior of the longitudinals, the transversals, and the plating. Difficulties in the tests arising from local crippling of the stiffeners are also discussed.